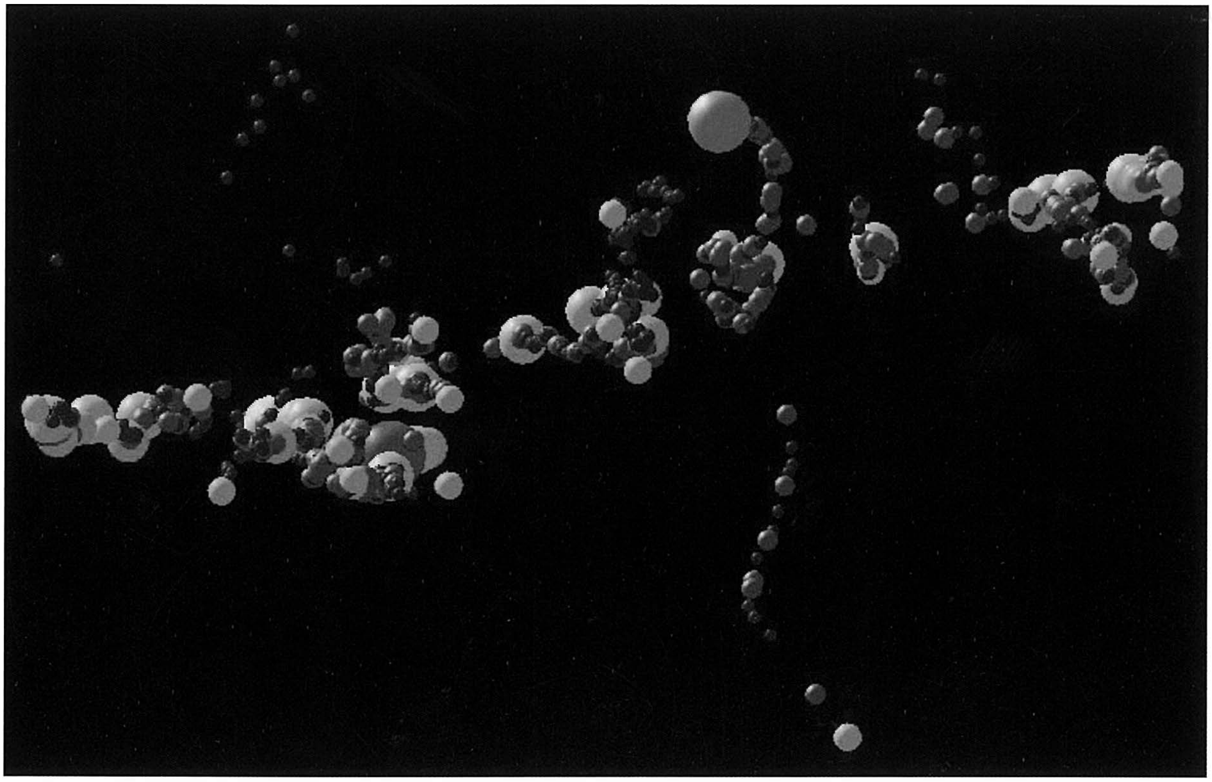
BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

68th Annual Gaseous Electronics Conference held jointly with 9th Annual International Conference on Reactive Plasma & 33rd Symposium on Plasma Processing

October 12-16, 2015

Honolulu, Hawaii



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Please Note: APS has made every effort to provide accurate and complete information in this *Bulletin*. However, changes or corrections may occasionally be necessary and may be made without notice after the date of publication. To ensure that you receive the most up-to-date information, please check the meeting Corrigenda distributed with this *Bulletin*, the Meeting App, the Meeting Website, or the "Program Changes" board located near Registration.

68th Annual Gaseous Electronics Conference held jointly with 9th Annual International Conference on Reactive Plasma & 33rd Symposium on Plasma Processing

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68th Annual Gaseous Electronics Conference held jointly with 9th Annual International Conference on Reactive Plasma & 33rd Symposium on Plasma Processing

October 12–16, 2015

Honolulu, Hawaii

GENERAL INFORMATION

The 68th Gaseous Electronics Conference (GEC) will take place October 12-16, 2015, in Hawaii, U.S.A., as a joint conference with the 9th International Conference on Reactive Plasmas (ICRP) and the 33rd Symposium on Plasma Processing (SPP). This is the third joint meeting of GEC/ICRP after Maui (Hawaii, 1998) and Paris (France, 2010). The conference will be held at the Hawaii Convention Center in Honolulu.

The GEC is a special conference of the American Physical Society, which promotes the exchange of scientific information and viewpoint concerning basic phenomena in the field of gaseous electronics. It has been held annually since 1948. The ICRP has taken place by the initiative of the Division of Plasma Electronics, the Japan Society of Applied Physics, since 1991. The SPP is known as an annual Japanese domestic meeting, which has also been held by the Division of Plasma Electronics since 1984.

The subjects covered in this joint conference are the entire field of gaseous electronics, including charged-particle collisions, reactive plasmas, and their applications to various materials processing such as surface modification, etching and deposition with emphasis on basic phenomena, technologies, and the underlying basic physics and chemistry. Furthermore, the subjects have been extended to bio- and/or medical applications of plasmas. This conference particularly encourages papers dealing with basic properties of the plasma itself, its generation and control, fundamental processes in the plasma, and plasma-solid/liquid interactions.

The ICRP-9/GEC-68/SPP-33 will consist of a series of oral sessions (composed of both invited and contributed papers), poster sessions, and several arranged sessions on selected topics. Sessions will be organized around coherent subjects in order to facilitate useful discussions and focus on appropriate solutions to problems.

The official language of the conference is English. It will be used for all presentations and printed materials.

The conference will bring together over 500 scientists and engineers from around the world who will attend 65 invited talks, 270 oral contributed talks, and 323 poster presentations. The GEC program includes a preconference workshop on Monday, an opening reception on Monday evening, two workshops on Tuesday and Wednesday evening, the Foundation Talk on Wednesday morning, and a Thursday evening awards banquet. An ICRP plenary talk will also be presented on Wednesday morning.

The GEC prides itself in student attendance. We will also present the "Student Award for Excellence" to the best student oral presentation, selected from a group of five finalists.

SPECIAL SESSIONS AND EVENTS

The GEC Executive Committee is pleased to announce that the GEC Foundation Talk will be presented by Timothy Gay from the University of Nebraska at Lincoln. His talk entitled "The Gaseous Electronics Conference in its seventh decade: some new problems in an old field" is scheduled for 11:00 am on Wednesday, October 10. The ICRP plenary talk, entitled "Plasma-surface interactions for top-down and bottom-up nanofabrication", will be presented by Kouichi Ono from Kyoto University at 10:00 am on Wednesday, October 10.

Several workshops will be held during the conference:

SESSION AM1:
Challenge of Plasma Science towards Future Medicine I
Monday, October 8 • 1:00 pm

SESSION AM2:
Challenge of Plasma Science towards Future Medicine II
Monday, October 8 • 3:30 pm

SESSION HT1:
Atomic and Molecular Scattering Data for Plasma and Related Applications I
Tuesday, October 9 • 8:00 pm

SESSION MW1:
Atomic and Molecular Scattering Data for Plasma and Related Applications II
Wednesday, October 10 • 8:00 pm

SESSION NUMBERING SCHEME

Each session has a code consisting of a letter and a number. The first letter indicates the numbering for that session in the program, e.g., A for 1, B for 2, etc. The second letter indicates the day of the week: M for Monday, T for Tuesday, W for Wednesday, R for Thursday, and F for Friday. The last number indicates the room location of the oral presentations: 1 for 301 B, 2 for 308 AB, 3 for 305 AB, and 4 for 303 AB. The plenary session will take place in room 311, and the poster sessions will be held in Exhibit Hall III.

PRESENTATION FORMAT

Papers that have been accepted for presentations are listed in the scientific program. Invited talks are allotted 25 minutes, with 5 additional minutes for questions and discussion. Oral contributed talks are allotted 12 minutes, with 3 additional minutes for questions and discussion. Poster boards measure 4 feet (height) by 8 feet (width). The posters may remain on display throughout the day and should be removed at the close of each day.

GEC STUDENT AWARD FOR EXCELLENCE

The GEC Executive Committee will award a $1000 prize for best oral presentation by a student. Their advisor must have nominated a student before being selected by GEC Executive Committee members to present and compete for the Excellence Award. Student award finalists will present their work on Tuesday, October 13 and Wednesday, October 14. Students competing for the award, in the order of their appearance in the GEC 2015 program are:

Sandra Schröter, University of York
"Reactive species generated in atmospheric-pressure plasmas with water admixtures for biomedical applications: Absolute measurements and numerical simulations"
Tuesday, Oct. 13 • 8:30 am in 305 AB

Bastien Bruneau, Ecole Polytechnique, University Paris-Saclay
"Comparison of the effect of sawtooth-like voltage waveforms on discharge dynamics of Ar, H2, and CF4 plasmas"
Tuesday, Oct. 13 • 11:00 am in 308 AB

Jan Trieschmann, Ruhr-Universität Bochum
"Negative Power Absorption in Low-Pressure Inductive Discharges"
Tuesday October 13 • 1:30 pm in 308 AB

Keishiro Tamura, Tokyo Institute of Technology
"Transient Analysis of Pulsed Dry Methane Reforming in DBD-Catalyst Hybrid Reaction"
Wednesday, Oct. 14 • 2:00 pm in 301 B

Jannis Teunissen, Eindhoven Univ of Technology
"Advances in the three-dimensional simulation of streamer discharges"
Wednesday, Oct. 14 • 3:15 pm in 305 AB

At the 2014 GEC in Raleigh North Carolina, the GEC Student Award for Excellence was presented to Andrew Gibson, Queen's University Belfast, for the oral presentation "Tailoring plasma properties through the non-linear frequency coupling of odd harmonics".

REGISTRATION

The registration desk will be will located in Room 301A, Hawaii Convention Center, Level 3. The registration desk will be open on Monday, October 12 from 11:00 am to 5:00 pm. Tuesday through Friday, the registration desk will be open from 7:00 am to 4:00 pm. The on-site registration fees are:

Regular Attendee	$700
Retired/Unemployed	$350
Student	$350
One-Day Attendee	$400
Guest Banquet Ticket	$100
Guest Reception Ticket	$60

OPENING RECEPTION AND BANQUET

An opening reception will be held from 6:00 pm to 8:00 pm on Monday, October 12, in Room 311, Hawaii Convention Center. On Thursday evening, October 15, the banquet featuring live entertainment and awards presentations will be held from 6:00 to 9:00 pm on the Rooftop Garden, Hawaii Convention Center. The cost of the banquet is included in the attendee's registration fee. Banquet and reception guest tickets may be purchased for $100 (banquet) and $60 (reception) at the registration desk on-site through the end of the day on Tuesday, October 13. All conference attendees and guests are encouraged to attend. The GEC and ICRP Awards for Best Student Oral and Poster Presentations will be presented during the banquet.

WI-FI AND OTHER SERVICES

Wi-Fi access is complimentary in the sleeping rooms at the Ala Moana Hotel and meeting areas at the Hawaii Convention Center. For a fee, services such as faxing, printing, and photocopying are available in the Business Center located at the Hawaii Convention Center, Level 3.

AUDIO – VISUAL EQUIPMENT

The technical sessions will be equipped with an LCD projector and amplified sound. Laptops will be provided for the technical sessions. All laptops will be equipped with Windows 7, PowerPoint, Acrobat Reader, QuickTime, and Windows Media player. Presentations need to be uploaded before the session to the laptop provided. Experience shows that saving your presentation as a PDF file avoids potential conversion problems between PC and Macintosh computers. If presenters wish/need to use their own computer, any setup delay will be counted against their allotted presentation time.

DINING OPTIONS

The Ala Moana Hotel offers a wide range of dining choices perfectly suited to every taste while maintaining a decidedly serene ambience in the heart of the city. Treat the entire family to breakfast at the Plantation Café. Enjoy Chinese cuisine at the Royal Garden or healthful Japanese food at Yuzu. Spend an evening at Rumours, a fun Honolulu nightclub. The Waikiki neighborhood is Honolulu's center for sampling a diverse selection of food, walking along the iconic crescent beach backed by palms, shopping, and nightlife, with volcanic Diamond Head looming in the distance.

CALL FOR NOMINATIONS FOR GEC GENERAL AND EXECUTIVE COMMITTEES

The GEC Executive Committee welcomes nominations, including self-nominations, for both the General Committee and the Executive Committee. Becoming a General Committee and/or Executive Committee member provides a unique opportunity to see both how the GEC is governed and how one may influence GEC's future direction by helping to define scientific programs and select future venues. This includes selection of special event topics, invited speakers, abstract sorting categories, arranging the technical program, selection of meeting sites, and budgetary decisions.

Please submit your nominations to the GEC Chair or any member of the Executive Committee. At the GEC Business Meeting nominations will be accepted to select five new members of the GEC General Committee. The General Committee meets once a year during the GEC. The Executive Committee meets twice a year, once during the GEC and once during the summer at the Sorters Meeting.

Written proposals to host future GEC meetings are encouraged and should be discussed with the Chair of the Executive Committee. The General Committee reviews all proposals and makes the final site selection. The selected host is then elected to a 3-year term on the Executive Committee as Secretary-Elect, then Secretary, and finally as Past Secretary. The 2015 Business Meeting will take place on Wednesday, October 14 immediately following the Foundation Talk in Room 311.

CALL FOR INVITED SPEAKER RECOMMENDATIONS FOR THE 69TH GEC (BOCHUM, GERMANY, 2016)

This year, the GEC Executive Committee will solicit recommendations for invited speakers from GEC participants. As specified in the GEC constitution, the Executive Committee will make the final selection of invited speakers.

PUBLICATION OF INVITED SPEAKER ARTICLES IN PLASMA SOURCES, SCIENCE, AND TECHNOLOGY

All GEC invited speakers are invited to submit their conference article to the Plasma Sources, Science, and Technology journal. The articles will be reviewed to the usual Journal standards and published as regular papers. Once all the articles are published they will be gathered in a web page dedicated to the 68th GEC and free to download for a period of time. This year, the Guest Editors are Ugo Ancarani (Université de Lorraine) and Costel Biloiu (Applied Materials). Please contact the Guest Editors to submit your GEC invited talk article to the Journal.

GEC 2015 EXECUTIVE COMMITTEE

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GEC 2015 SPONSORS AND EXHIBITORS

Sponsors and Exhibitors allow the GEC Executive Committee to provide many benefits to attendees including travel assistance and an excellence award for junior attendees. The 68th GEC has been fortunate to receive support from the following organizations (up to the time of this publication.) GEC is very grateful for the continued support from government and industry.

Sponsors

GOLD SPONSORS ($5,000 OR MORE):

Tokyo Electron Limited
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Engineering Systems International Group
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Due to generous support of sponsors, we have been able to accommodate most student requests for travel assistance!

PLEASE NOTE

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Epitome of the 2015 Annual Fall Meeting of the Gaseous Electronics Conference

13:00 MONDAY AFTERNOON
12 OCTOBER 2015

AM1 **Challenge of Plasma Science towards Future Medicine Workshop I**
Shinya Toyokuni, Klaus-Dieter Weltmann, Alexander Fridman, Eun Ha Choi
Room: 301 B

15:30 MONDAY AFTERNOON
12 OCTOBER 2015

BM1 **Challenge of Plasma Science towards Future Medicine Workshop II**
Nobuyuki Shimizu, Eric Robert, David Graves
Room: 301 B

18:00 MONDAY EVENING
12 OCTOBER 2015

CM2 **Opening Reception**
Room: 311

08:00 TUESDAY MORNING
13 OCTOBER 2015

DT1 **Plasma Thrusters**
Room: 301 B

DT2 **Plasma Surface Interactions I**
Osamu Sakai
Room: 308 AB

DT3 **Optical Diagnostics I**
Natalia MacDonald-Tenenbaum
Room: 305 AB

DT4 **Basic Low Pressure Plasma Physics**
Room: 303 AB

10:00 TUESDAY MORNING
13 OCTOBER 2015

ET1 **Reactive Species for Plasma Medicine**
Deborah O'Connell, Ryo Ono
Room: 301 B

ET2 **Capacitively Coupled Plasmas I**
Erik Johnson
Room: 308 AB

ET3 **Diagnostic Probes**
David Gahan
Room: 305 AB

ET4 **Positron and Electron Collisions**
C.M. Surko, James Sullivan
Room: 303 AB

13:30 TUESDAY AFTERNOON
13 OCTOBER 2015

FT1 **Plasma Medicine**
Thomas von Woedtke
Room: 301 B

FT2 **Inductively Coupled Plasmas**
Room: 308 AB

FT3 **Microplasmas**
Mikhail Benilov
Room: 305 AB

FT4 **Thermal Plasmas; Materials Applications**
Jochen Schein
Room: 303 AB

16:00 TUESDAY AFTERNOON
13 OCTOBER 2015

GT1 **Poster Session I (4:00pm - 6:00 pm)**
Room: Exhibit Hall III

20:00 TUESDAY EVENING
13 OCTOBER 2015

HT1 **Atomic and Molecular Scattering Data for Plasma and Related Applications Workshop I**
Igor Bray, Oleg Zatsarinny, Mark J. Kushner, Hiroshi Tanaka
Room: 301 B

08:00 WEDNESDAY MORNING
14 OCTOBER 2015

IW1 **Disinfection/Sterlization by Plasma**
Masaaki Nagatsu
Room: 301 B

IW2 **Ion Assisted Deposition**
Room: 308 AB

IW3 **Modeling and Simulation I**
Keith Cartwright, Andrew Christlieb
Room: 305 AB

IW4 **Electron and Photon Collisions**
Joan Dreiling, Bruno deHarak
Room: 303 AB

10:00 WEDNESDAY MORNING
14 OCTOBER 2015

JW1 **GEC & ICRP Plenary Sessions, Business Meeting**
Kouichi Ono, Timothy Gay
Room: 311

13:30 WEDNESDAY AFTERNOON
14 OCTOBER 2015

KW1 **Plasma Gas Conversion**
Gerard van Rooij
Room: 301 B

KW2 **Magnetically Enhanced Plasmas**
Hirotake Sugawara
Room: 308 AB

KW3 **Modeling and Simulation II**
Jan Trieschmann
Room: 305 AB

KW4 **Atmospheric & Thermal Plasmas**
Masaya Shigeta, Peter Bruggeman
Room: 303 AB

16:00 WEDNESDAY AFTERNOON
14 OCTOBER 2015

LW1 **Poster Session II (4:00pm - 6:00pm)**
Room: Exhibit Hall III

20:00 WEDNESDAY EVENING
14 OCTOBER 2015

MW1 **Atomic and Molecular Scattering Data for Plasma and Related Applications Workshop II**
Yuri Ralchenko, Hajime Tanuma, Predrag Krstic
Room: 301 B

08:00 THURSDAY MORNING
15 OCTOBER 2015

NR1 **Plasma Sources for Biomedical Applications I**
Volker Schulz-von der Gathen, Stephan Reuter
Room: 301 B

NR2 **Plasma CVD/Radical Assisted CVD**
Room: 308 AB

NR3 **Plasma Sheaths and Boundary Layers**
John Caughman
Room: 305 AB

NR4 **Plasma-Assisted Combustion**
Room: 303 AB

10:00 THURSDAY MORNING
15 OCTOBER 2015

OR1 **Plasma Interaction with Liquids I**
Room: 301 B

OR2 **Plasma Etching I**
Demetre Economou, Nobuyuki Kuboi
Room: 308 AB

OR3 **Atmospheric Discharges: Pulses and Streamers**
Anne Bourdon, Kentaro Tomita
Room: 305 AB

OR4 **Electron-Impact Ionization**
Masahiko Takahashi, Don Madison
Room: 303 AB

13:30 THURSDAY AFTERNOON
15 OCTOBER 2015

PR1 **Atmospheric Plasmas I**
Timo Gans
Room: 301 B

PR2 **Capacitively Coupled Plasmas II**
Room: 308 AB

PR3 **Gas Phase Plasma Chemistry**
Room: 305 AB

PR4 **Electron Collisions**
Michael Fogle, Marco Lima
Room: 303 AB

15:30 THURSDAY AFTERNOON
15 OCTOBER 2015

QR1 **Plasma Interaction with Liquids II**
David Go, Yongfeng Li
Room: 301 B

QR2 **Plasmas for Nanotechnologies**
Holger Kersten
Room: 308 AB

QR3 **Negative Ion and Dust Particle Containing Plasmas**
Room: 305 AB

QR4 **Modeling and Simulation III**
Luis Chacon
Room: 303 AB

08:00 FRIDAY MORNING
16 OCTOBER 2015

SF1 **Atmospheric Plasmas II**
Room: 301 B

SF2 **Carbon Related Materials Deposition**
Room: 308 AB

SF3 **Optical Diagnostics II**
Ximing Zhu
Room: 305 AB

SF4 **Plasma Surface Interactions II**
Room: 303 AB

10:00 FRIDAY MORNING
16 OCTOBER 2015

TF1 **Plasma Interaction with Liquids III**
Room: 301 B

TF2 **Plasma Etching II**
Deirdre Olynick
Room: 308 AB

TF3 **Applications of Plasmas**
Sylvain Coulombe
Room: 305 AB

TF4 **Atmospheric Pressure Plasma Jets**
Laxminarayan L. Raja
Room: 303 AB

13:30 FRIDAY AFTERNOON
16 OCTOBER 2015

UF1 **Plasma Sources for Biomedical Applications II**
Vittorio Colombo, Koichi Takaki
Room: 301 B

UF2 **Diffuse Discharges**
David Smith
Room: 308 AB

UF3 **Nonequilibrium Kinetics of Low-Temperature Plasmas**
Room: 305 AB

UF4 **Heavy-Particle Collisions and Swarms**
Thomas Schlathoelter, Tom Kirchner
Room: 303 AB

15:30 FRIDAY AFTERNOON
16 OCTOBER 2015

WF1 **Plasma Thrusters and Flow Control**
Room: 301 B

WF2 **Magnetron Sputter Deposition**
Jyh-Ming Ting
Room: 308 AB

WF3 **Dielectic Barrier Discharges**
Hindrik de Vries, Francesco Fracassi
Room: 305 AB

WF4 **Biomedical Applications**
Farzaneh Arefi, Eun Ha Choi
Room: 303 AB

SESSION AM1: CHALLENGE OF PLASMA SCIENCE TOWARDS FUTURE MEDICINE WORKSHOP I

Monday Afternoon, 12 October 2015
Room: 301 B at 13:00
Toshiro Kaneko, Tohoku University, presiding

Contributed Papers

13:00
AM1 1 Opening Remarks

Invited Papers

13:05
AM1 2 Non-thermal Plasma and Oxidative Stress
SHINYA TOYOKUNI, *Nagoya University, Japan*

Thermal plasmas and lasers have been used in medicine to cut and ablate tissues and for coagulation. Non-equilibrium atmospheric pressure plasma (NEAPP; non-thermal plasma) is a recently developed, non-thermal technique with possible biomedical applications. Although NEAPP reportedly generates reactive oxygen/nitrogen species, electrons, positive ions, and ultraviolet radiation, few research projects have been conducted to merge this technique with conventional free radical biology. Recently, Prof. Masaru Hori's group (Plasma Nanotechnology Research Center, Nagoya University) developed a NEAPP device with high electron density. Here electron spin resonance revealed hydroxyl radicals as a major product. To merge non-thermal plasma biology with the preexisting free radical biology, we evaluated lipid peroxidation and DNA modifications in various in vitro and ex vivo experiments. Conjugated dienes increased after exposure to linoleic and alfa-linolenic acids. An increase in 2-thiobarbituric acid-reactive substances was also increased after exposure to phosphatidylcholine, liposomes or liver homogenate. Direct exposure to rat liver in medium produced immunohistochemical evidence of 4-hydroxy-2-nonenal- and acrolein-modified proteins. Exposure to plasmid DNA induced dose-dependent single/double strand breaks and increased the amounts of 8-hydroxy-2′-deoxyguanosine and cyclobutane pyrimidine dimers. These results indicate that oxidative biomolecular damage by NEAPP is dose-dependent and thus can be controlled in a site-specific manner. Simultaneous oxidative and UV-specific DNA damage may be useful in cancer treatment. Other recent advancements in the related studies of non-thermal plasma in Nagoya University Graduate School of Medicine will also be discussed.

[1]Okazaki *et al.*, J. Clin. Biochem. Nutr. **55**, 207 (2014).
[2]S. Toyokuni *et al.*, FEBS Lett. **358**, 1 (1995).

13:35
AM1 3 Plasma Sources for Medical Applications - A Comparison of Spot Like Plasmas and Large Area Plasmas
KLAUS-DIETER WELTMANN, *INP Greifswald*

Plasma applications in life science are currently emerging worldwide. Whereas today's commercially available plasma surgical technologies such as argon plasma coagulation (APC) or ablation are mainly based on lethal plasma effects on living systems, the newly emerging therapeutic applications will be based on selective, at least partially non-lethal, possibly stimulating plasma effects on living cells and tissue. Promising results could be obtained by different research groups worldwide revealing a huge potential for the application of low temperature atmospheric pressure plasma in fields such as tissue engineering, healing of chronic wounds, treatment of skin diseases, tumor treatment based on specific induction of apoptotic processes, inhibition of biofilm formation and direct action on biofilms or treatment of dental diseases. The development of suitable and reliable plasma sources for the different therapies requires an in-depth knowledge of their physics, chemistry and parameters. Therefore much basic research still needs to be conducted to minimize risk and to provide a scientific fundament for new plasma-based medical therapies. It is essential to perform a comprehensive assessment of physical and biological experiments to clarify minimum standards for plasma sources for applications in life science and for comparison of different sources. One result is the DIN-SPEC 91315, which is now open for further improvements. This contribution intends to give an overview on the status of commercial cold plasma sources as well as cold plasma sources still under development for medical use. It will discuss needs, prospects and approaches for the characterization of plasmas from different points of view. Regarding the manageability in everyday medical life, atmospheric pressure plasma jets (APPJ) and dielectric barrier discharges (DBD) are of special interest. A comprehensive risk-benefit assessment including the state of the art of commercial sources for medical use will be discussed.

14:05
AM1 4 Plasma Onco-Immunotherapy: Novel Approach to Cancer Treatment
ALEXANDER FRIDMAN, *Drexel University*

Presentation is reviewing the newest results obtained by researchers of A.J. Drexel Plasma Institute on direct application of non-thermal plasma for direct treatment of different types of cancer by means of specific stimulation of immune system in the frameworks of the so-called onco-immunotherapy. Especial attention is paid to analysis of depth of penetration of different plasma-medical effects, from ROS, RNS, and ions to special biological signaling and immune system related processes. General aspects of the plasma-stimulation of immune system are discussed, pointing out specific medical applications. Most of experiments have been carried out using nanosecond pulsed DBD at low power and relatively low level of treatment doses, guaranteeing non-damage no-toxicity treatment regime. The nanosecond pulsed DBD physics is discussed mostly regarding its space uniformity and control of plasma parameters relevant to plasma medical treatment, and especially relevant to depth of penetration of different plasma medical effects. Detailed mechanism of the plasma-induced onco-immunotherapy has been suggested based upon preliminary in-vitro experiments with DBD treatment of different cancer cells. Sub-elements of this mechanism related to activation of macrophages and dendritic cells, specific stressing of cancer cells and the immunogenic cell death (ICD) are to be discussed based on results of corresponding in-vitro experiments. In-vivo experiments focused on the plasma-induced onco-immunotherapy were carried out in collaboration with medical doctors from Jefferson University hospital of Philadelphia. Todays achievements and nearest future prospective of clinical test focused on plasma-controlled cancer treatment are discussed in conclusion.

14:35

AM1 5 Scientific Reports of Plasma Medicine and its Mechanism for Therapy in Plasma Bioscience Research Center
EUN HA CHOI, *Kwangwoon University, Korea*

Scientific reports of plasma medicine and its basic mechanism for therapy will be introduced, especially, performed in Plasma Bioscience Research Center, Korea. We have investigated enhanced anticancer effect of monocytes and macrophages activated by nonthermal plasma which act as immune-modulator on these immune cells. Further, we investigated the action of the nanosecond pulsed plasma activated media (NPPAM) on the lung cancer cells and its DNA oxidation pathway. We observed OD induced apoptosis on melanocytes G361 cancer cells through DNA damage signaling cascade. We also studied DNA oxidation by extracting DNA from treated cancer cell and analyzed the effects of OD/OH/D_2O_2/H_2O_2 on protein modification and oxidation. Additionally, we attempted molecular docking approaches to check the action of D_2O_2 on the apoptosis related genes.

SESSION BM1: CHALLENGE OF PLASMA SCIENCE TOWARDS FUTURE MEDICINE WORKSHOP II
Monday Afternoon, 12 October 2015; Room: 301 B at 15:30; Mounir Laroussi, Old Dominion University, presiding

Invited Papers

15:30

BM1 1 Systematization of the Mechanism by Which Plasma Irradiation Causes Cell Growth and Tumor Cell Death
NOBUYUKI SHIMIZU, *International University of Health and Welfare/Sanno Hospital, Japan*

New methods and technologies have improved minimally invasive surgical treatment and saved numerous patients. Recently, plasma irradiation has been demonstrated that might be useful in medical field and the plasma irradiation device is expected to become practically applicable. Mild plasma coagulator showed some advantages such as hemostasis and adhesion reduction in experimental animal model, but the mechanism of plasma irradiation remains unclear. Our study group aim to clarify the mechanism of plasma irradiation effects, mainly focusing on oxidative stress using cultured cell lines and small animal model. First, a study using cultured cell lines showed that the culture medium that was activated by plasma irradiation (we called this kind of medium as "PAM" -plasma activated medium-) induced tumor cell death. Although this effect was mainly found to be due to hydrogen peroxide, the remaining portion was considered as the specific effect of the plasma irradiation and we are now studying focusing on this effect. Second, we established a mouse intra-peritoneal adhesion model and checked biological reaction that occurred in the adhesion part. Histopathological study showed inflammatory cells infiltration into adhesion part and the expression of PTX3 that might involve tissue repair around adhesion part. We also confirmed that cytokines IL-6 and IL-10 might be useful as a marker of adhesion formation in this model. Applying "PAM" or mild plasma irradiation in this model, we examine the effects of plasma on inflamed cells. The samples in these experiments would be applied to targeted proteomics analysis, and we aim to demonstrate the systematization of the cell's reaction by plasma irradiation.

16:00

BM1 2 Gas Flow and Electric Field Characterization in Plasma Jets for Biomedical Applications: From Single Jet to Multi Jet Arrays
ERIC ROBERT, *GREMI, France*

This work reports first on time-resolved measurement of longitudinal and radial electric fields (EF) associated with plasma propagation in dielectric capillaries. Plasma propagation occurs in a region where longitudinal EF exists ahead the ionization front position revealed from plasma emission with ICCD measurement. The ionization front propagation induces the sudden rise of a radial EF component. Both of these EF components have a few kV/cm in amplitude for helium or neon plasmas. Their amplitude is kept almost constant along a few tens of cm long capillary. The key role of the voltage pulse polarity and the drastic impact of the presence of a target in front of the plasma jet are discussed from

Schlieren images. All these experimental measurements are in excellent agreement with model calculations which are used to infer EF data on capillary axis. EF diagnostics in the plasma plume in the free jet mode but also in contact with various targets is proposed. The combination of intense transient EF, both of ns and μs duration, together with significant transient reactive species generation during plasma jet treatments may be reconsidered. Typical EF amplitudes likely to induce electrostimulation, electroporation are indeed probably achieved in many in vivo protocols. Stimulation of tissue oxygenation, blood flow rate modulation and more recently immune system triggering may be examples where EF could play a significant role. The second part of this work is dedicated to the development of multi jets, using two different setups, based on a single plasma source. Plasma splitting in dielectric tubes drilled with sub millimetric orifices, but also plasma transfer across metallic tubes equipped with such orifices are analyzed from ICCD imaging and time resolved EF measurements. This allows for the design of plasma jet arrays but also emphasizes the necessity to account for voltage pulse polarity, target potential status, consecutive helium flow modulation and electrostatic influence between the produced secondary jets. The development of plasma arrays based on combination of plasma splitting within dielectric tubes and plasma transfer across metallic tube is reported leading to the generation of tens of secondary jets from a single PG device, i.e a single DBD reactor flushed with 2 l/mn of helium.

16:30
BM1 3 Mechanisms of Plasma Therapeutics
DAVID GRAVES, *University of California, Berkeley*

In this talk, I address research directed towards biomedical applications of atmospheric pressure plasma such as sterilization, surgery, wound healing and anti-cancer therapy. The field has seen remarkable growth in the last 3-5 years, but the mechanisms responsible for the biomedical effects have remained mysterious. It is known that plasmas readily create reactive oxygen species (ROS) and reactive nitrogen species (RNS). ROS and RNS (or RONS), in addition to a suite of other radical and non-radical reactive species, are essential actors in an important sub-field of aerobic biology termed "redox" (or oxidation-reduction) biology. It is postulated that cold atmospheric plasma (CAP) can trigger a therapeutic shielding response in tissue in part by creating a time- and space-localized, burst-like form of oxy-nitrosative stress on near-surface exposed cells through the flux of plasma-generated RONS. RONS-exposed surface layers of cells communicate to the deeper levels of tissue via a form of the "bystander effect," similar to responses to other forms of cell stress. In this proposed model of CAP therapeutics, the plasma stimulates a cellular survival mechanism through which aerobic organisms shield themselves from infection and other challenges.

Contributed Papers

17:00
BM1 4 Closing remarks

SESSION CM2: OPENING RECEPTION
Monday Evening, 12 October 2015; Room: 311 at 18:00;

Contributed Papers

11:30
CM2 1 Reception

SESSION DT1: PLASMA THRUSTERS
Tuesday Morning, 13 October 2015
Room: 301 B at 8:00
Tatsuo Ishijima, Kanazawa University, presiding

Contributed Papers

8:00
DT1 1 Phase-resolved emission spectroscopy of a neutraliser-free gridded ion thruster* JAMES DEDRICK, *York Plasma Institute, University of York* ANDREW GIBSON, *York Plasma Institute, University of York and Laboratoire de Physique des Plasmas (LPP-CNRS), Ecole Polytechnique* DMYTRO RAFALSKYI, ANE AANESLAND, *Laboratoire de Physique des Plasmas (LPP-CNRS), Ecole Polytechnique* Power-efficient electric propulsion systems that operate without an external neutraliser have the potential to increase the longevity of traditional concepts. The Neptune gridded-ion thruster prototype, which uses a single radio-requency (rf) power source for plasma generation, ion acceleration and beam neutralisation, is under development. Previous research has suggested that the time-resolved electron dynamics in the plume are important for maintaining charge neutrality and overall performance. In this study, the electron dynamics in the exhaust beam are investigated within the rf cycle using phase-resolved emission spectroscopy. The results are compared with time-resolved and time-integrated electrical diagnostics to investigate the mechanisms behind beam neutralisation.

*This work received financial support from the York-Paris CIRC and state aid managed by the laboratory of excellence Plas@Par (ANR-11-IDEX-0004-02).

8:15
DT1 2 Increasing Extracted Beam Current Density in Ion Thrusters through Plasma Potential Modification NEIL ARTHUR, JOHN FOSTER, *University of Michigan* A gridded ion thruster's maximum extractable beam current is determined by the space charge limit. The classical formulation does not take into account finite ion drift into the acceleration gap. It can be shown that extractable beam current can be increased beyond the conventional Child-Langmuir law if the ions enter the gap at a finite drift speed. In this work, ion drift in a 10 cm thruster is varied by adjusting the plasma potential relative to the potential at the extraction plane. Internal plasma potential variations are achieved using a novel approach involving biasing the magnetic cusps. Ion flow variations are assessed using simulated beam extraction in conjunction with a retarding potential analyzer. Ion beam current density changes at a given total beam voltage in full beam extraction tests are characterized as a function of induced ion drift velocity as well.

8:30
DT1 3 Cathode-less gridded ion thrusters for small satellites* ANE AANESLAND, DMYTRO RAFALSKYI, *LPP - Ecole Polytechnique* We present here a new gridded ion thruster, called Neptune, that operates with only one Radio Frequency (RF) power source for ionization, ion acceleration and beam neutralization in addition to solid iodine as propellant. Thus significant simplifications, over excising gridded thrusters, might allow downscaling to satellites as small as 6 kg. The combined acceleration and neutralization is achieved by applying an RF voltage to the grid system via a blocking capacitor. As for similar RF capacitive systems, a self-bias is formed such that ions are continuously accelerated while electrons are emitted in brief instants within the RF sheath collapse. Moreover, the RF nature of the acceleration system leads to a higher space charge limited current extracted across the grids compared to classical DC operated systems. Measurements of the ion and electron energy distribution functions in the plasma plume show that in addition to the directed beam of ions, the electrons are also anisotropic resulting in a flowing plasma, rather than a beam of positive ions. Experimental characterization of this RF accelerated plume is detailed.

*This work received financial state aid managed by the ANR as part of the program "Investissements d'avenir" under the reference ANR-11-IDEX-0003-02 (Project MINIATURE).

8:45
DT1 4 Particle-in-Cell Simulation of a Micro ECR Plasma Thruster KEISUKE UENO, DAISUKE MORI, YOSHINORI TAKAO, KOJI ERIGUCHI, KOUICHI ONO, *Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University* Downsizing spacecrafts has recently been focused on to decrease mission costs and to increase launch rates, and missions with small satellites would bring a great advantage of reducing their risks. Such a concept supports a new approach to developing precise, reliable, and low-cost micropropulsion systems. We have developed a new type of electromagnetic micro plasma thruster using electron cyclotron resonance (ECR) discharges. The microthruster consists of a microwave antenna and a quartz microplasma chamber 4.15 mm in inner diameter surrounded by two permanent magnet rings. The plasma is generated by 4-GHz microwaves of < 10 W with a propellant gas of Xe, where the ions are accelerated through divergent magnetic fields and the resulting ambipolar electric fields generated. To investigate plasma characteristics of the thruster, we simulated the plasma density, electrostatic potential, and ion velocity in the exhaust area by the particle-in-cell (PIC) method with a Monte Carlo calculation for particle collisions, where the electrostatic field and the ion velocity were obtained by solving the Poisson equation and the equation of motion, respectively. The numerical results showed that the ions generated in the plasma are well confined by the applied magnetic fields and diffuse out of the discharge tube, then being accelerated by a potential drop of $\sim$7 V through divergent magnetic fields from < 1000 to > 3000 m/s (< 0.7 to > 6 eV) in the axial direction.

9:00
DT1 5 Energetic ion production in high current hollow cathodes* JOHN FOSTER, YAO KOVACH, NEIL ARTHUR, ERIC VIGES, CHRIS DAVIS, *The University of MIchigan-Ann Arbor* High power Hall and gridded ion thrusters are being considered as a propulsion option supporting human operations (cargo or tug) to Mars. These engines utilize hollow cathodes for plasma production and beam neutralization. It has now been well documented that these cathodes produce energetic ions when operated at high current densities. Such ions are observed with peak energies approaching 100 eV. Because these ions can drive erosion of the cathode assembly, they represent a credible failure mode. An understanding of energetic ion production and approaches to mitigation is therefore desired. Presented here are data documenting the presence of energetic ions for both a barium oxide and a lanthanum hexaboride cathode as measured using a retarding potential analyzer. Also presented are energetic ion mitigation approaches, which are designed to eliminate the ion energy transfer mechanism.

*NASA SBIR Contract NNX15CP62P.

9:15
DT1 6 Simulation of Magnetic Field Guided Plasma Expansion FRANS EBERSOHN, J.P. SHEEHAN, ALEC GALLIMORE,

University of Michigan JOHN SHEBALIN, *NASA Johnson Space Center* Magnetic field guided expansion of a radio-frequency plasma was simulated with a quasi-one-dimensional particle-in-cell code. Two-dimensional effects were included in a one-dimensional particle-in-cell code by varying the cross-sectional area of the one dimensional domain and including forces due to the magnetic field. Acceleration of electrons by the magnetic field forces leads to the formation of potential structures which then accelerate the ions into a beam. Density changes due to the plasma expansion only weakly affect the ion acceleration. Rapidly diverging magnetic fields lead to more rapid acceleration and the electrons cool as they expand.

SESSION DT2: PLASMA SURFACE INTERACTIONS I

Tuesday Morning, 13 October 2015; Room: 308 AB at 8:00; Toshihiko Iwao, Tokyo Electron Inc., presiding

Invited Papers

8:00

DT2 1 Negative-permittivity plasma generation in negative-permeability metamaterial space
OSAMU SAKAI, *The University of Shiga Prefecture*

Negative-permittivity plasma is generated in negative-permeability metamaterial space. Unlike cases of positive permeability, which is quite usual in almost all materials available so far, negative-permeability space realized in metamaterial structure [1] allows microwaves to propagate in negative-permittivity media. Our previous study [2, 3] verified that microwaves can propagate in a negative-permittivity plasma immersed in a negative-permeability metamaterial space, which indicates that a dynamic state of negative refractive index was successfully generated. In this study, negative-permeability space was prepared using metamaterial structure as well, and we investigated plasma generation by high-power microwaves in such a metamaterial structure. Langmuir probe measurement revealed that electron density is higher than the cutoff density, which means that permittivity is negative [4, 5]. We also confirmed in both model predictions [6] and experimental results [4, 5, 7] that nonlinear phenomena are key issues to understand underlying physics; they include bifurcations of permittivity or electron density in nonlinear dynamics and harmonic wave generation similar to that reported in nonlinear optics, and both phenomena are observed in experiments.

[1] J. B. Pendry *et al.*, IEEE Trans. Microw. Theory Techniq. **47**, 2075 (1999).
[2] O. Sakai and K. Tachibana, Plasma Sources Sci. Technol. **21**, 013001 (2013).
[3] O. Sakai *et al.*, Phys. Plasmas **20**, 073506 (2013).
[4] Y. Nakamura and O. Sakai, Jpn. J. Appl. Phys. **53**, 03DB04 (2014).
[5] Y. Nakamura, A. Iwai, and O. Sakai, Plasma Sources Sci. Technol. **23**, 064009 (2014).
[6] O. Sakai, J. Appl. Phys. **109**, 084914 (2011).
[7] A. Iwai, N. Nakamura, A. Bambina, and O. Sakai, Appl. Phys. Express **8**, 056201 (2015).

Contributed Papers

8:30

DT2 2 Numerical modeling of plasma meta-materials for electromagnetic energy flow control* KONSTANTINOS KOURTZANIDIS, DYLAN PEDERSON, LAXMINARAYAN RAJA, *The University of Texas at Austin* Meta-materials are a new and promising technology that could enable advances in several scientific fields – especially in electromagnetic (EM) energy flow control. These materials though present a major drawback: They can only interact with a limited range of EM frequencies and their structure is pre-defined, rendering them non-tunable and non-reconfigurable. Instead of using structural crystal patterns as in common meta-materials, micro-plasma discharges can be used to control the EM energy propagation. Plasmas present resonant frequencies depending on their degree of ionization – their charged particles density. By adjusting the plasma density, different EM wave frequencies can be manipulated – controlled. In this article, we present 2D and 3D numerical results of plasma meta-materials and their interaction with high frequency (HF) EM waves. Maxwell's equations are coupled with the electron momentum equation and a quasi-neutral fluid description for the plasma dynamics. We study the interaction between a plasma array and HF EM waves demonstrating significant reduction in the transmitted EM energy. Remote ignition of the plasma micro-discharges by the EM waves is also numerically investigated in a simplified configuration.

*Supported by the Air Force Office of Scientific Research (AFOSR) through a Multi-University Research Initiative (MURI) grant titled "Plasma-Based Reconfigurable Photonic Crystals and Metamaterials" with Dr. Mitat Birkan as the program manager.

8:45

DT2 3 Carrier transport and trapping in a-Si:H films under plasma processing SHOTA NUNOMURA, ISAO SAKATA, KOJI MATSUBARA, *National Institute of Advanced Industrial Science and Technology* Carrier transport is an important factor that determines the performances of solar cells and transistors [1]. It is often limited by carrier trapping, associated with various defects. The defects are created during fabrication processes using various plasmas; however the defect creation kinetics is not known. Here, we demonstrate the detection of the trapped carriers in a-Si:H films under plasma enhanced CVD, and discuss the carrier trapping and defect kinetics. Using an optically pump-probe technique, we detected the trapped carriers in an a-Si:H films during growth by plasma enhanced CVD [2]. An a-Si:H film growing on a glass substrate was illuminated with pump and probe light. The photocurrent induced by the pump was measured throughout the growth and post-growth annealing [3]. An increment in the photocurrent induced by the pulsed probe was also measured. The trapped carrier density was determined from the increment since it originates from detrapping of carriers. We found that the trapped carrier density was typically $10^{18}\mathrm{cm}^{-3}$. It was dependent on the growth temperature, and minimized at 473K. Interestingly, the detected trapped carriers were distributed uniformly in the direction of growth, and they were reduced during postgrowth annealing.

[1]S. Nunomura *et al.*, Adv. Mater. **26**, 7555 (2014).
[2]S. Nunomura *et al.*, AIP Advances **4**, 097110 (2014).
[3]S. Nunomura *et al.*, Appl. Phys. Express. **6**, 126201 (2013).

9:00

DT2 4 Damage formation mechanisms of Si and Ge substrates by ion bombardment MASAAKI MATSUKUMA, TAMOTSU MORIMOTO, *Tokyo Electron Limited* MICHIRO ISOBE, KAZUHIRO KARAHASHI, SATOSHI HAMAGUCHI, *Osaka University* Recently the choice of materials for most advanced semiconductor devices, which typically have three dimensional (3D) structures rather than planer ones, has been changing from silicon to III-V compounds or germanium. Such changes have brought renewed interest in physical damages caused by ion bombardment because, in typical gate etching processes of 3D devices, the channel surfaces are exposed directly to the ion irradiation from the plasma. The angles of ion incidence on 3D device gates can be much larger than those on 2D planer devices. Therefore a better control of the damage layer formation on modern 3D devices requires a better understanding of the damage formation mechanisms on such new materials and structures. In this study, damage formation processes by energetic ion bombardment have been simulated for Si/Ge/SiGe substrates by molecular dynamics (MD) simulations and dependence of ion induced damages on species of incident ions and their doses has been examined. Based on the simulations results, damage formation mechanisms will be discussed and a semi-analytical model to predict the damage extent formed by ion bombardment will be also presented.

9:15

DT2 5 Mechanisms of Hydrocarbon Based Polymer Etch BARTON LANE, PETER VENTZEK, *Tokyo Electron America* MASAAKI MATSUKUMA, AYUTA SUZUKI, *TEL Technology Development Center, Yamanashi* AKIRA KOSHIISHI, *TEL Process Module Technology Department, Miyagi* Dry etch of hydrocarbon based polymers is important for semiconductor device manufacturing. The etch mechanisms for oxygen rich plasma etch of hydrocarbon based polymers has been studied but the mechanism for lean chemistries has received little attention. We report on an experimental and analytic study of the mechanism for etching of a hydrocarbon based polymer using an Ar/O2 chemistry in a single frequency 13.56 MHz test bed. The experimental study employs an analysis of transients from sequential oxidation and Ar sputtering steps using OES and surface analytics to constrain conceptual models for the etch mechanism. The conceptual model is consistent with observations from MD studies and surface analysis performed by Vegh *et al.* and Oehrlein *et al.* [1,2] and other similar studies. Parameters of the model are fit using published data and the experimentally observed time scales.

[1]J. J. Vegh, D. Nest, D. B. Graves, R. Bruce, S. Englemann, T. Kwon, R. J. Phaneuf, G. S. Oehrlein, B. K. Long, and C. G. Willson, J. Appl. Phys. **104**, 034308 (2008).
[2]G. S. Oehrlein, R. J. Phaneuf, and D. G. Graves, J. Vac. Sci. Tech. B **29**, 010801 (2011).

9:30

DT2 6 The Effect of N2 Plasma on Atomic Hydrogen Surface Recombination S. SMITH, C.Y. TAI, *MKS Instruments* Remote plasma sources are increasingly being used with reducing chemistries for radical generation in on wafer applications. The repeatability of atomic hydrogen output from wafer to wafer and matching of performance between chambers is paramount and is a topic that receives a great deal of attention. The atomic radical recombination on plasma facing surfaces is known to have a strong impact on hydrogen radical output of remote plasma sources. Presented here are results showing that the source output can be attenuated by up to 40% as a result of exposing the surface to nitrogen plasma, which chemically modified the wall resulting in a high recombination surface. It is also shown that subsequent hydrogen processing can convert the surface back to its low recombination state. Additionally this "seasoning" or "conditioning" effect is shown to be on a time scale of days. Measurements of radical concentrations were made with a calorimeter; surface analysis is done with XPS as well as high resolution SEM.

SESSION DT3: OPTICAL DIAGNOSTICS I

Tuesday Morning, 13 October 2015; Room: 305 AB at 8:00; Ursel Fantz, Max Planck Institute for Plasma Physics, presiding

Invited Papers

8:00

DT3 1 Laser Diagnostics for Spacecraft Propulsion
NATALIA MACDONALD-TENENBAUM, *Air Force Research Laboratory*

Over the past several decades, a variety of laser diagnostic techniques have been developed and applied to diagnose spacecraft propulsion devices. Laser diagnostics are inherently non-intrusive, and provide the opportunity to probe properties such as temperature, concentration or number density of plume species, and plume velocities in the harsh environments of combustion and plasma discharges. This presentation provides an overview of laser diagnostic capabilities for spacecraft propulsion devices such as small monopropellant thrusters, arcjets, ion engines and Hall thrusters. Particular emphasis is placed on recent developments for time-resolved ion velocity measurements in Hall thruster plumes. Results are presented for one such diagnostic method, a time-synchronized CW-laser induced fluorescence (LIF) technique based on a sample hold scheme. This method is capable of correlating measured fluorescence excitation lineshapes with high frequency current fluctuations in the plasma discharge of a Hall thruster and is tolerant of natural drifting in the current oscillation frequency [1].

[1]N. A. MacDonald, M. A. Cappelli, and W. A. Hargus Jr., Rev. Sci. Instrum. **83**, 113506 (2012).

Contributed Papers

8:30

DT3 2 Student Award Finalist: Reactive species generated in atmospheric-pressure plasmas with water admixtures for biomedical applications: Absolute measurements and numerical simulations* SANDRA SCHRÖTER, J. BREDIN, A. WEST, K. NIEMI, J. DEDRICK, *University of York* N. DE OLIVEIRA, D. JOYEUX, L. NAHON, *Synchrotron SOLEIL* M. FOUCHER, J.-P. BOOTH, *LPP-CNRS* E. WAGENAARS, T. GANS, D. O'CONNELL, *University of York* We investigate the production of atomic oxygen (O), hydroxyl (OH) and atomic hydrogen (H) in an rf atmospheric-pressure plasma operated in helium with water admixtures. These species, and their longer-lived products, are known to influence biological systems. Absolute measurements of species densities are required to develop these plasmas for therapeutics. Accurate determination of radical densities is challenging at elevated pressures in complex gas mixtures due to collisional quenching. We measure radical densities using VUV high-resolution Fourier-transform absorption spectroscopy with synchrotron radiation, UV broadband absorption spectroscopy, and picosecond two-photon absorption laser induced fluorescence (ps-TALIF). These diagnostics are the most suitable techniques allowing direct, absolute and 2-dimensional spatial resolution measurements at atmospheric pressure. Ps-TALIF also enables measurements of the lifetimes of laser-excited states of O and H, providing insight into the chemical kinetics and ambient air diffusion into the plasma jet region. Good agreement has been found between the measurements and a numerical chemical-kinetic simulation.

*Funding from the UK EPSRC (EP/K018388/1 & EP/H003797/1), the York-Paris Low Temperature Plasma Collaborative Research Centre and financial state aid managed by the laboratory of excellence Plas@Par (ANR-11-IDEX-0004-02).

8:45

DT3 3 Development and Calibration of Electron Density Measurements in Argon Plasma Using Laser Collision-Induced Fluorescence* ED BARNAT, *Sandia National Laboratories* BRANDON WEATHERFORD, *L-3 Communications, Electron Devices Division* Laser collision-induced fluorescence (LCIF) is a powerful diagnostic which can be used for making temporally and spatially resolved measurements of electron densities in a plasma discharge. The technique, which involves the measurement of optical emission emanating from higher energy excited states due to the redistribution of the lower energy laser-excited state by collisions with energetic electrons, has been readily employed to study argon discharges. In this work, we report on recent efforts to extend the LCIF technique to argon based plasma systems. Discussion will be offered on the spectroscopic pathway used for the interrogation of argon and discussion will be given on the procedures used to calibration the LCIF diagnostic. Particular emphasis will be placed on the double-pulse excitation of a plasma column that enables near independent control of electron density and electron energy. Anticipated bounds on the range of application of the calibrated transitions will likewise be discussed. Finally, the utility of the LCIF diagnostic will be demonstrated by applying the technique to spatially and temporally varying plasma systems.

*This work was supported by the Department of Energy Office of Fusion Energy Science Contracts DE-AC04-94SL85000 and DE-SC0001939.

9:00

DT3 4 Influence of Molecular Gas Concentration on Measurement of Plasma Electron Density by Saturation Spectroscopy S. NISHIYAMA, H. WANG, K. SASAKI, *Hokkaido University* Recently, we applied saturation spectroscopy to electron density measurement of argon plasmas. In general, the peak height of saturation spectrum or the saturation parameter is a function of the relaxation frequency of related energy levels. In the case of the metastable level of argon in argon plasma, the relaxation frequency is dominated by electron impact quenching, hence we can deduce the electron density from the saturation parameter. On the other hand, in the case of mixture plasma of argon and molecular gas, molecular species also contribute to the relaxation frequency of the metastable level. In this study, we investigated the influence of molecular gas concentration on the electron density measurement. An ICP source was used for producing argon-nitrogen and argon-hydrogen mixture plasmas. The frequency of a tunable diode laser was scanned over the Doppler width of the $4s[3/2]_2^o - 4p[3/2]_2$ transition (763.51 nm). We confirmed a linear relationship between the inverse of the saturation parameter and the electron density in the argon-nitrogen mixture plasma. However, the linear relationship was not found in the argon-hydrogen mixture plasma. The breakdown of the linear relationship is caused by the change in the density of molecular hydrogen due to dissociation.

9:15

DT3 5 Plasma Propagation Speed Model For Electron Temperature Investigated Of Ar And N_2 In Atmospheric Pressure Non-Thermal Indirect-Plasma Jet PRADOONG SUANPOOT, *Maejo University Phrae Campus* JIRAPONG SORNSAKDANUPHAP, GOOK-HEE HAN, HAN-SUP UHM, GUANG-SUP CHO, EUN-HA CHOI, *Department of Electrical and Biological Physics, and Plasma Bioscience Research Center, Kwangwoon University* Space and time resolved discharge images from an atmospheric pressure non-thermal indirect-plasma jet have been observed by a high-speed single-frame camera to investigate the electron temperatures. The propagation velocity of the indirect Ar and mixture N_2 (0 - 5%) plasmas along the plasma column has been shown to be in the order of 104 m/s, and that corresponds to an ion acoustic velocity in order of 102 m/s. Plasma has been generated by input discharge voltage of 3.0 kV at driving frequency of about 40 kHz. Particularly, there are two kinds of the electron, and it has been presented in atmospheric pressure non-thermal indirect-plasma jet. At slow electron energy, the average electron temperature has been found to be about 0.33 eV for Ar plasma and change to 0.42 eV for mixture Ar/N_2 plasma. And fast electron energy, the average electron temperature has been found to be about 1.19 eV for Ar plasma and change to 1.40 eV for mixture Ar/N_2 plasma. Implications of the results and directions for further studies are discussed.

SESSION DT4: BASIC LOW PRESSURE PLASMA PHYSICS

Tuesday Morning, 13 October 2015
Room: 303 AB at 8:00
Scott Baalrud, University of Iowa, presiding

Contributed Papers

8:00

DT4 1 Restructure of the plasma interior (presheath) caused by electron emission from surfaces* MICHAEL CAMPANELL, *Lawrence Livermore National Laboratory* In the conventionally theorized "space-charge limited" regime of strong electron emission, the sheath potential is negative and the presheath is governed by Bohm ion acceleration towards the sheath edge. However, recent works found that sheath potentials at emitting surfaces can be positive, repelling ions. In this "inverse sheath regime," the entire plasma interior (presheath) is also restructured [1]. Here we show at the presheath-sheath edge, due to their low velocities, the cold electrons entering the presheath have a higher spatial density than the hotter plasma electrons exiting the presheath. Therefore, assuming the emission collisionally thermalizes (reheats to the plasma temperature) in the presheath, it follows the quasineutral plasma density must increase towards the sheath edge, which is opposite from Bohm presheaths. The electron and ion force balance in the presheath becomes much different. A theoretical analysis with simulation and experimental evidence of "inverted presheaths" will be given. The results could be relevant to low temperature plasmas facing thermionically emitting surfaces and high temperature plasmas inducing strong secondary emission.

*This work was supported by the U.S. Department of Energy.

[1]M. D. Campanell, Phys. Plasmas **22**, 040702 (2015).

8:15

DT4 2 Influence of a phase-locked RF substrate bias on the E- to H-mode transition in an inductively coupled plasma PHILIPP AHR, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44780 Bochum* EDMUND SCHUENGEL, JULIAN SCHULZE, *Department of Physics, West Virginia University, WV 26506, USA* TSANKO V. TSANKOV, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44780 Bochum* The influence of a capacitive radio frequency substrate bias on the E- to H-mode transition and the electron heating dynamics in a low pressure inductively coupled plasma (ICP) in hydrogen is investigated. The inductive and capacitive power sources are driven at the same frequency and can be operated in a phase-locked mode with a fixed, but adjustable phase between them. This approach of phase-locked discharge operation is a new feature which enables time-resolved studies of both the inductive and the capacitive energy coupling by phase-resolved optical emission spectroscopy (PROES). The inductive power at which the mode transition occurs, P_{mtp}, is determined by PROES and from probe measurements of the electron density. For both, phase-locked and phase-unlocked operation, the plasma density in the E-mode is significantly influenced by the applied capacitive power: Already low values of bias power can reduce the value of P_{mtp}. This coupling between the power sources is dependent on the adjustable phase between them and is attributed to a phase sensitive confinement mechanism for the energetic electrons produced by the expanding sheaths at the substrate and at the ICP coil. At higher pressures the effect diminishes. In contrast, by using electrodes with ring-shaped trenches the coupling is enhanced.

8:30

DT4 3 Investigation of Self-Oscillation using Particle Balance Model* INSHIK BAE, BYUNGKEUN NA, HONGYOUNG CHANG,† *Korea Adv Inst of Sci & Tech* Self-oscillation, which is obtained by using a DC-only power supply with specific anode voltage conditions, is investigated in a cylindrical system with thermal electrons using tungsten filaments. From analysis of the obtained oscillation profiles, the experimental data is consistent with the model derived from the particle balance model. The self-oscillation period characteristics with respect to the pressure and gas species are also analyzed. As the physics and particle motion of self-oscillation near the electron avalanche is analyzed in different perspective, this study may advance the understanding of this phenomenon.

*This research was supported by the Ministry of Knowledge Economy (MKE) of Korea (Grant No. 10041681).
†academic adviser.

8:45

DT4 4 Measuring IVDF through high-aspect holes in pulsed ICP plasma* GILLES CUNGE, MAXIME DARNON, JEROME DUBOIS, PHILIPPE BEZARD, ODILE MOUREY, CAMILLE PETIT-ETIENNE, LAURENT VALLIER, EMILIE DESPIAU-PUJO, OLIVIER JOUBERT, NADER SADEGHI, *LTM-CNRS* Plasma etching of high aspect-ratio (AR) structures is challenging. Several issues originate from the ion angular distribution: the feature sidewalls are bombarded by energetic ions and the ion flux at the bottom of the features is reduced. In ICP reactors at low pressure, this angular dispersion is due to two effects: the finite transverse velocity component of the ions when they enter the sheath region (i.e. the ion temperature Ti in plasma bulk) and charging effect of the feature sidewalls. To analyze those effects, we have measured the IVDF at the wafer surface in an industrial ICP reactor (AMAT) by using Semion multigrid ion energy analyzers. The plasma is operated in different chemistries (Ar, He, H_2 and CF_4) both in CW and pulsed mode. To analyze ion transport through high AR holes, we place 0.4 mm thick capillary plates with holes of AR 16, 8 and 4 in front of the RFA analyzer, which then probe IVDF at the exit of these holes. The results show that the ion flux drops dramatically when the AR is increased. By comparing the measured IVDF with an analytical model which calculates the transmission of a hole as a function of its AR and of T_i we concluded that Ti is about 3000 K. Charging effects are also observed and are shown to reduce significantly the ion energy at the feature bottom but with a "minor" effect on the ion flux and shape of the IVDF. We will discuss electropositive versus electronegative gases, pulsing and the role of ion mass on charging.

*This project is funded by the French Agence Nationale de la Recherche in the frame of the project clean GRAPH (ANR-13-BS09-0019).

9:00

DT4 5 Anomalous electron transport in magnetized plasmas with ExB drift A. SMOLYAKOV, W. FRIAS, I. ROMADANOV, *University of Saskatchewan, Saskatoon SK, Canada* I. KAGANOVICH, Y. RAITSES, *Princeton Plasma Physics Laboratory, Princeton NJ, USA* M. UMANSKY, *Lawrence Livermore National Laboratory, Livermore CA, USA* Nonlinear fluid model has been developed for describing the fluctuations in Hall plasmas with magnetized electrons and non-magnetized ions. The plasma is immersed in externally applied crossed electric and magnetic fields. Plasma density gradient and collision destabilize the anti-drift and low hybrid modes resulting in turbulence. The conditions for excitation are tested with initial value simulations within the BOUT++ framework and with a linear eigenvalue solver. Nonlinear turbulence simulations are performed and levels of the anomalous transport are determined. The scalings of the turbulent transport with various plasma parameters are investigated. Nonlinear fluid simulations are compared with selected results of Particle-in-Cell simulations.

9:15

DT4 6 Ion particle and energy flux uniformity control using a phase locked dual ICP coil design DAVID COUMOU, *MKS Instruments, ENI Power Division* STEVEN SHANNON, *NC State University, Department of Nuclear Engineering* Phase lock drive of multiple power sources to drive a single plasma discharge has demonstrated the ability to modify low pressure discharges in a variety of ways not achievable by other means including control of electrical asymmetry ion energy distribution function shape and uniformity. This work presents an experimental effort to elucidate the relationship between plasma parameters and locked phase between dual inductive coils and between the coils and bias cathode of a commercial 300 mm etching chamber. Adjusting parameters to maintain a constant electron density at the center of the discharge, both ion flux uniformity and average ion energy are impacted by these relative phase conditions.

SESSION ET1: REACTIVE SPECIES FOR PLASMA MEDICINE

Tuesday Morning, 13 October 2015; Room: 301 B at 10:00; David Graves, University of California Berkeley, presiding

Invited Papers

10:00
ET1 1 TBD
DEBORAH O'CONNELL, *University of York*

Contributed Papers

10:30
ET1 2 Reactive species profile in an atmospheric pressure plasma jet ignited in He and He/O2 mixture – implications for surface sterilization KRISHNA PRIYA ARJUNAN, BRENDAN JONES, SYLWIA PTASINSKA, *Radiation Laboratory, University of Notre Dame* The enhanced chemistry and low temperature of cold atmospheric plasma (CAP) makes it a promising alternative to conventional sterilization techniques. Of the various configurations used for generating cold plasma, atmospheric pressure plasma jets (APPJs) are particularly interesting for biomedical applications since they can be used for targeted treatment of intricate geometries such as catheters due to their small dimensions. The present study shows the efficacy of an APPJ ignited in helium or He/O_2 mixture in inactivating *Escherichia coli* (*E.coli*) bacterium on agar plate. To study the dependence of helium flow rate and sample distance on the inactivation area, *E.coli* spread on agar was treated for 10 min at various combinations of helium flow rates and sample distances from the nozzle. A ring-shaped inactivation area was observed in samples treated close to the jet nozzle. Addition of O_2 significantly increased the inactivation area. The ring shaped inactivation area observed with only helium feed gas vanished with oxygen addition. The optical emission spectra of the core and jet region of the APPJ in helium and He/O_2 were obtained. The profile of H_2O_2, NO_2-, NO_2- and O_2 reaching the sample were determined using test strips arranged in a 3×3 array. A ring-shaped profile was observed for these species in samples treated close to the nozzle with helium APPJ, while no ring-shaped profile was observed with O_2 addition. Addition of O_2 increased O_2 levels, and was detected up to 3 cm in the radial direction.

10:45
ET1 3 Controlling Fluences of Reactive Species Produced by Multipulse DBDs onto Wet Tissue: Frequency and Liquid Thickness* WEI TIAN, MARK J. KUSHNER, *University of Michigan* Tissue covered by a thin liquid layer treated by atmospheric pressure plasmas for biomedical applications ultimately requires a reproducible protocol for human healthcare. The outcomes of wet tissue treatment by dielectric barrier discharges (DBDs) depend on the plasma dose which determines the integral fluences of radicals and ions onto the tissue. These fluences are controlled in part by frequency and liquid thickness. In this paper, we report on results from a computational investigation of multipulse DBDs interacting with wet tissue. The DBDs were simulated for 100 stationary or random streamers at different repetition rates and liquid thicknesses followed by 10 s to 2 min of afterglow. At 100 Hz, NO_{aq} and OH_{aq} are mixed by randomly striking streamers, although they have different rates of solvation. NO_{aq} is nearly completely consumed by reactions with OH_{aq} at the liquid surface. Only H_2O_{2aq}, produced through OH_{aq} mutual reactions, survives to reach the tissue. After 100 pulses, the liquid becomes ozone-rich, in which the nitrous ion, $NO^-_{2\,aq}$, is converted to the nitric ion, $NO^-_{3\,aq}$. Reducing the pulse frequency to 10 Hz results in significant fluence of NO_{aq} to the tissue as NO_{aq} can escape during the interpulse period from the liquid surface where OH_{aq} is formed. For the same reason, $NO^-_{2\,aq}$ can also reach deeper into the liquid at lower frequency. Frequency and thickness of the liquid are methods to control the plasma produced aqueous species to the underlying tissue.

*Work supported by DOE (DE-SC0001319) and NSF (CHE-1124724).

11:00
ET1 4 Effect of active species on animal cells in culture media induced by DBD Plasma irradiation using air TETSUYA OHTSUBO, REOTO ONO, NOBUYA HAYASHI, *Kyushu University* Little has been reported on action mechanism of active species produced by plasmas affecting living cells. In this study, active species in culture medium generated by torch type DBD and variations of animal cells are attempted to be clarified. Animal cells are irradiated by DBD plasma through various media such as DMEM, PBS and distilled water. Irradiation period is 1 to 15 min. The distance between the lower tip of plasma touch and the surface of the medium is 10 mm. Concentrations of NO_2-, O_2 in liquid are measured. After the irradiation, the cells were cultivated in culture medium and their modifications are observed by microscope and some chemical reagents. Concentration of NO_2- and H_2O_2 in all media increased with discharge period. Increase rate of NO_2-concentration is much higher than that of hydrogen peroxide. After plasma irradiation for 15 min, concentrations of NO_2 were 80 mg/L in DMEM, 30 mg/L in PBS and 15 mg/L in distilled water. Also, the concentration of H_2O_2 became 3mg/L in DMEM, 6.5 mg/L in PBS and 6.5mg/L in distilled water. The significant inactivation of cells was observed in the PBS. Above results indicate that, in this experiment, H_2O_2 or OH radicals would affect animal cells in culture media.

11:15
ET1 5 Characterization of Wet Air Plasma Jet Powered by Sinusoidal High Voltage and Nanosecond Pulses for Plasma Agricultural Application* KEISUKE TAKASHIMA, KEISUKE SHIMADA, HIDEAKI KONISHI, TOSHIRO KANEKO, *Department*

of Electronic Engineering, Tohoku University Not only for the plasma sterilization but also for many of plasma life-science applications, atmospheric pressure plasma devices that allowed us to control its state and reactive species production are deserved to resolve the roles of the chemical species. Influence of the hydroxyl radical and ozone on germination of conidia of a strawberry pathogen is presented. Water addition to air plasma jet significantly improves germination suppression performance, while measured reactive oxygen species (ROS) are reduced. Although the results show a negative correlation between ROS and the germination suppression, this infers the importance of chemical composition generated by plasma. For further control of the plasma product, a plasma jet powered by sinusoidal high voltage and nanosecond pulses is developed and characterized with the voltage–charge Lissajous. Control of breakdown phase and discharge power by pulse-imposed phase is presented.

*This work is supported by JSPS KAKENHI Grant-in-Aid for Young Scientists (B) Grant Number 15K17480 and Exploratory Research Grant Number 23644199.

Invited Papers

11:30

ET1 6 Measurement of reactive species for plasma medicine

RYO ONO, *The University of Tokyo*

Plasma medicine has been intensively studied over the last decade. Reactive oxygen and nitrogen species are responsible for the therapeutic effects in plasma medicine. To examine the therapeutic effects of reactive species, the densities of OH, O, and NO were measured using laser-induced fluorescence (LIF). A helium atmospheric-pressure plasma jet (10 kV, 10 kHz of 40 μs pulses) and a nanosecond streamer discharge (24 kV, 8 ns, 30 Hz) were utilized to treat mouse melanoma cells in a culture medium. Correlation between the dose of reactive species and deactivation rate of melanoma cells was measured with the aid of LIF. The results showed that the rate of cell death correlates with OH density, but not with O and NO densities. Next, a method to supply a specific reactive species to living organisms was developed. It utilizes photolysis of helium-buffered H_2O and O_2 by vacuum ultraviolet (VUV) light to produce reactive species. The VUV method was utilized to sterilize *Bacillus atrophaeus* on agar plate. With the VUV method, it was succeeded to show sterilization only by OH radicals. A 30 s treatment with approximately 0.1 ppm OH radicals caused visible sterilization.

SESSION ET2: CAPACITIVELY COUPLED PLASMAS I
Tuesday Morning, 13 October 2015; Room: 308 AB at 10:00; Pascal Chabert, Ecole Polytechnique, presiding

Invited Papers

10:00

ET2 1 Gaining greater control and understanding of processing plasmas through Tailored Voltage Waveforms

ERIK JOHNSON, *LPICM-CNRS, Ecole Polytechnique*

The use of multiple harmonics of an RF frequency to generate the exciting voltage waveform for a capacitively coupled plasma has in recent years become a rich and diverse field of research. Initially proposed, observed, and named as the Electrical Asymmetry Effect by the Bochum group, the use of such Tailored Voltage Waveforms to sustain a plasma has gone beyond asymmetrizing the ion bombardment energy and flux to the electrodes. It is now clear that one can gain control over such plasma features as localization of ionization events and composition of species flux by using more counterintuitive waveforms. In this talk, progress in this field in three areas is discussed: (1) identification of new TVW's that give rise to more complex asymmetries (namely "slope-asymmetric" waveforms), (2) identifying applications of TVW's in plasma processing and metrology, and finally, (3) solving the technical challenges of using the technique in an industrially feasible way. The talk will focus on work done at the LPICM and LPP CNRS laboratories at the Ecole Polytechnique, but in collaboration with a number of partners from other institutes.

Contributed Papers

10:30

ET2 2 Control of electron heating and ion energy distributions in capacitive plasmas by voltage waveform tailoring based on a novel power supply and impedance matching BIRK BERGER, JAMES FRANEK, STEVEN BRANDT, *West Virginia University* MARTIN LIESE, MATTHIAS BARTHEL, *Barthel HF* EDMUND SCHUENGEL, MARK KOEPKE, JULIAN SCHULZE, *West Virginia University* We present a novel RF power supply and impedance matching to drive technological plasmas with customized voltage waveforms. By adjusting the individual phases and amplitudes of multiple consecutive harmonics any voltage waveform can be realized as a customized finite Fourier series. This RF supply system is easily adaptable to any technological plasma for industrial applications and allows the commercial utilization of process optimization based on voltage waveform tailoring for the first time. Here, this system is tested on a capacitive discharge based on three consecutive harmonics of 13.56 MHz in argon. The effect of changing the shape of the driving voltage waveform on the electron heating and sheath dynamics is investigated by Phase Resolved Optical Emission Spectroscopy (PROES) for different electrode gaps, pressures, and applied voltages. At low pressure the results are correlated with ion energy distribution functions measured at both electrodes. Tuning the phases between the applied harmonics results in an electrical control of the DC self-bias and the mean ion energy. A comparison with the reference case of a dual-frequency discharge reveals that using more than two consecutive harmonics significantly enlarges the control range of the mean ion energy.

10:45

ET2 3 Control of electron heating dynamics and DC self bias in electronegative capacitive CF_4 plasmas by voltage waveform tailoring JULIAN SCHULZE, *West Virginia University* BASTIEN BRUNEAU, ERIK JOHNSON, JEAN-PAUL BOOTH, TREVOR LAFLEUR, *Ecole Polytechnique* IHOR KOROLOV, ARANKA DERZSI, ZOLTAN DONKO, *Hungarian Academy of Sciences* STEVEN BRANDT, EDMUND SCHUENGEL, *West Virginia University* ARTHUR GREB, DEBORAH O'CONNELL, TIMO GANS, *York Plasma Institute* The effect of tailoring the driving voltage waveform on the electron heating dynamics and the generation of a DC self bias in multi-frequency capacitive CF_4 plasmas is investigated by a combination of Phase Resolved Optical Emission Spectroscopy, voltage measurements, and kinetic PIC/MCC simulations. One electrode is driven by up to 5 consecutive harmonics of different fundamental frequencies (3 MHz - 13.56 MHz). By adjusting the harmonics' phases and amplitudes different waveforms (peaks, valleys, sawtooths) are realized and found to strongly affect the spatio-temporal excitation dynamics and the electrical generation of a DC self bias via the Electrical Asymmetry Effect. For a given waveform, increasing the pressure induces an electron heating mode transition from the α- to the Drift-Ambipolar mode due to an increase of the electronegativity. For sawtooth waveforms, the ionization induced asymmetry and the polarity of the DC self bias are found to be reversed at high pressures compared to electropositive gases. At high frequencies the simulations show that the discharge can be split into two halves of different electronegativity, which can be controlled by tailoring the driving voltage waveform.

11:00

ET2 4 Student Award Finalist: Comparison of the effect of sawtooth-like voltage waveforms on discharge dynamics of Ar, H_2, and CF_4 plasmas BASTIEN BRUNEAU, E. JOHNSON, *LPICM-CNRS, Ecole Polytechnique, France* T. GANS, D. O'CONNELL, A. GREB, *York Plasma Institute, Univ. of York, UK* I. KOROLOV, A. DERZSI, Z. DONKO, *Wigner Research Centre for Physics, Budapest, Hungary* E. SCHUNGEL, S. BRANDT, J. SCHULZE, *Dept of Physics, West Virginia Univ., USA* P. DIOMEDE, D.J. ECONOMOU, *Plasma Processing Laboratory, Univ. of Houston, USA* S. LONGO, *Dipartimento di Chimica dell' Universita' di Bari, Italy* T. LAFLEUR, J.-P. BOOTH, *LPP-CNRS, Ecole Polytechnique, France* The use of Tailored Voltage Waveforms to excite a plasma has been previously shown to efficiently control the ion energy (through the Electrical Asymmetry Effect) by varying the "amplitude" asymmetry of the waveform. In this work, the effect of a "slope" asymmetry of the waveform is investigated by using sawtooth-like waveforms. When a discharge is excited with such a waveform, one sheath expands rapidly and contracts slowly, while the reverse occurs at the other sheath. While using such waveforms, different discharge gases are compared, namely Ar (as an electropositive gas), H2 (as a light gas), and CF4 (as an electronegative gas). For each gas, phase resolved optical emission spectroscopy measurements are compared with PIC simulations, showing excellent agreement. The dynamics of the excitation rates are very different for the different gases and are shown to be correlated with the dominant heating mechanisms. It is shown that the asymmetry obtained with sawtooth-like voltage waveforms can be very large, and can even be reversed, depending on the gas used.

11:15

ET2 5 Nonlinear standing wave excitation by series resonance-enhanced harmonics in low pressure capacitive discharges* M.A. LIEBERMAN, A.J. LICHTENBERG, EMI KAWAMURA, *University of California, Berkeley* A.M. MARAKHTANOV, *Lam Research Corporation* It is well known that standing waves having radially center-high rf voltage profiles exist in high frequency capacitive discharges. It is also known that in radially uniform discharges, the capacitive sheath nonlinearities excite strong nonlinear series resonance harmonics that enhance the electron power deposition. In this work, we consider the coupling of the series resonance-enhanced harmonics to the standing waves. A one-dimensional, asymmetric radial transmission line model is developed incorporating the wave and nonlinear sheath physics and a self-consistent dc potential. The resulting coupled pde equation set is solved numerically to determine the discharge voltages and currents. A 10 mT argon base case is chosen with plasma density 2×10^{16} m^{-3}, gap width 2 cm and conducting electrode radius 15 cm, driven by a high frequency 500 V source with source resistance 0.5 ohms. We find that nearby resonances lead to an enhanced ratio of 4.5 of the electron power per unit area on axis, compared to the average. The radial dependence of electron power with frequency shows significant variations, with the central enhancement and sharpness of the spatial resonances depending in a complicated way on the harmonic structure.

*Work supported by DOE Fusion Energy Science Contract DE-SC000193 and by a gift from the Lam Research Corporation.

11:30

ET2 6 Non-Linear Electron Resonance Heating in CCRF Discharges: A Kinetic Interpretation SEBASTIAN WILCZEK, JAN TRIESCHMANN, *Ruhr-University Bochum, Germany* JULIAN SCHULZE, EDMUND SCHUENGEL, *West Virginia University, Morgantown, USA* DENIS EREMIN, RALF PETER BRINKMANN, *Ruhr-University Bochum, Germany* ARANKA DERZSI, IHOR KOROLOV, PETER HARTMANN, ZOLTÁN DONKÓ, *Wigner Research Centre for Physics, Budapest, Hungary* THOMAS MUSSENBROCK, *Ruhr-University Bochum, Germany* In this work, the physical origin of non-linear electron resonance heating in capacitively coupled radio frequency discharges is investigated using Particle-in-Cell/Monte Carlo Collisions simulations. A detailed kinetic description of the electron dynamics is used to explain the mechanism of the excitation of harmonics in the rf current. It is shown that, especially at low pressures, highly energetic electrons are accelerated by the modulated plasma sheath and leave behind a positive space charge close to the sheath edge. Consequently, cold bulk electrons are attracted back towards this electron depleted zone. After a short time interval (defined by the local plasma frequency), bulk electrons reach the expanding sheath phase, are reflected, and gain energy forming a new energetic electron beam. Since such electron beams represent the major part of the conduction current, this mechanism leads to harmonics in the rf current. Finally, the question "In which way current continuity is ensured at all the times?" is answered.

11:45

ET2 7 Electron Heating Mode Transitions in Nitrogen (13.56 and 40.68) MHz RF-CCPs UMMUGUL EROZBEK GUNGOR, SINAN KADRI BILIKMEN, *Middle East Technical University* DEMIRAL AKBAR, *Hacettepe University* Capacitively coupled radio frequency plasmas (RF-CCPs) are commonly used in plasma material processing. Parametrical structure of the plasma determines the demands of processing applications. For example; high density plasmas in gamma mode are mostly preferred for etching applications while stabile plasmas in gamma mode are usually used in sputtering applications. For this reason, characterization of the plasma is very essential before surface modification of the materials. In this work, analysis of electron heating mode transition in high frequency (40.68 MHz) RF-CCP was deeply investigated. The plasma was generated in a home-made (500 × 400 mm^2) stainless steel cylindrical reactor in which two identical (200 mm in diameter) electrodes were placed with 40 mm interval. In addition, L-type automatic matching network system was connected to the 40.68 MHz RF generator to get high accuracy. Moreover, the pure (99.995 %) nitrogen was used as an activation gas on account of having an appreciable impression in plasma processing applications. Furthermore, diagnostic measurements of the plasma were done by using the Impedans Langmuir single and double probe systems. It was found that two transition points; α-γ (pressure dependent) and γ-α (RF power dependent) were observed in both medium and high RF-CCPs. As a result, the α-γ pressure transition increased, whereas the γ-α power transition remained constant by changing the RF frequency sources.

12:00

ET2 8 Electron Heating in Capacitively Coupled RF Discharges Investigated with the Smooth Step Model* RALF PETER BRINKMANN, *Ruhr University Bochum, Institute for Theoretical Electrical Engineering* Electron heating in radio-frequency driven capacitively coupled plasmas is studied on the basis of the recently proposed *Smooth Step Model* [1]. This algebraic model provides an expression for the electric field in a RF modulated plasma sheath transition which yields i) the space charge field in the sheath, ii) the generalized Ohmic and ambipolar field in the plasma, and iii) a smooth interpolation for the rapid transition in between. It was derived via an expansion of an electron fluid model in terms of two smallness parameters, the ratios $\epsilon = \lambda_D/l$ of the Debye length λ_D to the minimum gradient length l and $\eta = \omega_{RF}/\omega_{pe}$ of the RF frequency ω_{RF} to the electron plasma frequency ω_{pe}. The explicit field formula provided by the Smooth Step Model enables semi-analytic expressions for the phased-resolved and the phase-averaged dissipated power. Comparison with other models of electron heating is made.

*Deutsche Forschungsgemeinschaft (DFG) via Research Group FOR 1123 and Sonderforschungsbereich SFB-TR 87.

[1]R. P. Brinkmann, Plasma Sources Sci. Technol. (2015).

SESSION ET3: DIAGNOSTIC PROBES

Tuesday Morning, 13 October 2015
Room: 305 AB at 10:00
Edward Barnat, Sandia National Laboratories, presiding

Contributed Papers

10:00

ET3 1 Curling probe measurement of large-volume pulsed plasma confined by surface magnetic field ANIL PANDEY, *Chubu University* WATARU SAKAKIBARA, HIROYUKI MATSUOKA, *DOWA Thermotech* KEIJI NAKAMURA, HIDEO SUGAI, *Chubu University* CHUBU UNIVERSITY TEAM, DOWA THERMOTECH COLLABORATION *Curling probe* (CP) has recently been developed which enables the local electron density measurement even in plasma for non-conducting film CVD. The electron density is obtained from a shift of resonance frequency of spiral antenna in discharge ON and OFF monitored by a network analyzer (NWA). In case of a pulsed glow discharge, synchronization of discharge pulse with frequency sweep of NWA must be established. In this paper, we report time and space-resolved CP measurement of electron density in a large volume plasma (80 cm diameter, 110 cm length) confined by surface magnetic field (multipole cusp field ~0.03 T). For plasma-aided modification of metal surface, the plasma is produced by 1 kV glow discharge at pulse frequency of 0.3 – 25 kHz with various duty ratio in gas (Ar, N_2, C_2H_2) at pressure ~ 1 Pa. A radially movable CP revealed a remarkable effect of surface magnetic confinement: detach of plasma from the vessel wall and a fairly uniform plasma in the central region. In afterglow phase, the electron density was observed to decrease much faster in C_2H_2 discharge than in Ar discharge.

10:15

ET3 2 Electrostatic and Electromagnetic Resonances of the Curling probe ALI ARSHADI, *Institute for Theoretical Electrical Engineering, Ruhr University Bochum, Germany* LEILA VALADBEIGI, *Power Systems Technology and Power Mechatronics, Ruhr University Bochum, Germany* RALF PETER BRINKMANN, *Institute for Theoretical Electrical Engineering, Ruhr University Bochum, Germany* The term Active Plasma Resonance Spectroscopy denotes a class of plasma diagnostic techniques utilizing the natural ability of plasma to resonate on or near the electron plasma frequency: An electric signal in the GHz range is coupled into the plasma via a probe. The spectral response of the plasma is recorded and a mathematical model is used to find plasma parameters such as the electron density. The curling probe, recently invented by Liang *et al.*, is a novel realization of this concept which has many practical advantages. In particular, it can be miniaturized, and flatly embedded into the chamber wall, enabling monitoring of plasma processes without perturbing them. Physically, the curling probe can be seen as a "curled" form of the hairpin probe. Assuming that the effect of the spiralization is negligible, this work investigates the features of a "straightened" curling probe by modeling it as a slot-type resonator which is in contact with the plasma. The diffraction of an incident plane wave at the slot is calculated by solving Maxwell's equations and the cold plasma model simultaneously. Electrostatic and Electromagnetic resonances are derived. Good agreement of the analytically computed resonance frequencies with the numerical results of the probe inventors is shown.

10:30

ET3 3 Analyses of Different Techniques for the Plasma Probe Diagnostics VALERY GODYAK, *University of Michigan* BENJAMIN ALEXANDROVICH, *Plasma Sensors* The subject of this publication is comparison of the plasma parameters inferred from classical Langmuir probe procedure, from different theories of the ion current to the probe, and from measured EEDF using double differentiation of the probe characteristic We concluded that the plasma parameters inferred by the classical Langmuir procedure are subjected to significant inaccuracy due to non-Maxwellian EEDF, uncertainty of locating the plasma potential and arbitrariness in approximation of the ion current. The plasma density inferred from the ion part of the probe characteristic was found to diverge by as much as an order of magnitude from the density calculated as the EEDF integral, while the electron temperature is derived with significant uncertainty. Such inaccuracy is attributed to deficiencies in the ion current theories, i.e. unrealistic assumptions about Maxwellian-shaped EEDFs, underestimation of the ion collisions and the ion ambipolar drift, and some others. We concluded that for highly non-equilibrium gas discharge plasmas at low gas pressure the probe measurements based on EEDF diagnostics is single reliable tool of for the basic research and industrial applications. Examples of EEDF measurements reiterate significance of the instrument technical characteristics, such as high energy resolution and wide dynamic range and importance of displaying the probe current derivatives in real time.

10:45
ET3 4 Kinetic Damping in the Spectrum of the Spherical Impedance Probe* JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lueneburg, Germany* RALF PETER BRINKMANN, *Theoretical Electrical Engineering, Ruhr University Bochum, Germany* Active plasma resonance spectroscopy is a widely used diagnostic method and several probes in different designs have been invented. One of them is the Spherical Impedance Probe. Its resonance behavior and the influence of kinetic effects on it can be described by a general kinetic model presented by the authors [1]. It was theoretically shown that kinetic effects are responsible for a broadening of the resonance peak in the spectrum. However, the broadening of the resonance peak in a kinetically determined spectrum in the geometry of an existing probe is not evaluated, yet. We present such a spectrum of the Spherical Impedance Probe. Therefore, the general solution of the model is expanded in an orthonormal system of basis-functions. This expansion is truncated to determine an approximated spectrum. Its resonance peak shows clearly a broadening compared to a peak in a spectrum, which is determined by a fluiddynamical model.

*The authors acknowledge the support by the Research Service of Leuphana University Lueneburg, the Deutsche Forschungsgemeinschaft via the Ruhr University Research School and the Federal Ministry of Education and Research in frame of the PluTO+ projekt.

[1]J. Oberrath and R. P. Brinkmann, Plasma Sources Sci. Technol. **23**, 045006 (2014).

11:00
ET3 5 Using the Multipole Resonance Probe to Stabilize the Electron Density During a Reactive Sputter Process MORITZ OBERBERG, TIM STYRNOLL, STEFAN RIES, STEFAN BIENHOLZ, PETER AWAKOWICZ, *Ruhr-University Bochum* INSTITUTE OF ELECTRICAL ENGINEERING AND PLASMA TECHNOLOGY, RUHR-UNIVERSITY BOCHUM TEAM Reactive sputter processes are used for the deposition of hard, wear-resistant and non-corrosive ceramic layers such as aluminum oxide (Al_2O_3). A well known problem is target poisoning at high reactive gas flows, which results from the reaction of the reactive gas with the metal target. Consequently, the sputter rate decreases and secondary electron emission increases. Both parameters show a non-linear hysteresis behavior as a function of the reactive gas flow and this leads to process instabilities. This work presents a new control method of Al_2O_3 deposition in a multiple frequency CCP (MFCCP) based on plasma parameters. Until today, process controls use parameters such as spectral line intensities of sputtered metal as an indicator for the sputter rate. A coupling between plasma and substrate is not considered. The control system in this work uses a new plasma diagnostic method: The multipole resonance probe (MRP) measures plasma parameters such as electron density by analyzing a typical resonance frequency of the system response. This concept combines target processes and plasma effects and directly controls the sputter source instead of the resulting target parameters.

Invited Papers

11:15
ET3 6 Wireless sensor technology for in-situ plasma process monitoring
DAVID GAHAN, *Impedans Ltd*

There is an increasing demand for plasma measurement and control solutions to cope with the growing complexity of integrated circuit manufacture in the semiconductor industry. Standard plasma diagnostic instruments used in research, such as the Langmuir probe, are not suitable for use in the production environment for myriad reasons – contamination of the process being one of the main concerns. Silicon wafer based wireless sensors, which measure temperature during the process, have gained the most traction with tool manufacturers and chip makers – albeit during process development or the PM cycle rather than live production. In this presentation we will discuss two novel wireless technologies that have the potential for use in process tools. The first is an ion detector embedded in a silicon wafer. The sensor measures the average ion flux and the maximum ion energy during the process. This information is stored and is downloaded later for analysis. The second technology consists of a wireless sensor that sits inside the process and communicates data in real time to a detector installed on the rf power line. This platform is similar to RFID technology and can be combined with various sensor types to transmit data to the user during the process.

Contributed Papers

11:45
ET3 7 Phase-resolved measurement of surface charge deposition in a laterally patterned barrier discharge system* LARS STOLLENWERK, ROBERT WILD, *University of Greifswald, Inst. of Physics* In the present contribution a barrier discharge system with plane parallel electrodes is investigated. With appropriately chosen parameters, a patterned glow-like discharge arises. In the case of laterally inhomogeneous discharges (i.e. in the present patterned discharges or in the common filamentary discharges) also the surface charge distribution on the dielectric barriers is inhomogeneous. Due to its deformation of the electric field it provides a memory effect and thus contributes essentially to the stabilisation of the lateral structure. Therefor, the measurement of the surface charge has been come into focus in the last decade. In this contribution, spatially and temporally resolved electro-optical surface measurements are presented. The high temporal resolution allows for the first time the observation of the charge deposition during a single breakdown. The process starts in the center of a remnant surface charge spot,

where the electrical field is highest. The maximum of the electrical field then moves radially outwards. A surface charge spot is hence replaced from the inside out by a charge spot of opposite polarity. These experimental findings verify previously unconfirmed predictions from earlier numerical calculations.

*Funded by Deutsche Forschungsgemeinschaft, TR-24, B14.

SESSION ET4: POSITRON AND ELECTRON COLLISIONS
Tuesday Morning, 13 October 2015; Room: 303 AB at 10:00; Yuri Ralchenko, NIST, presiding

Invited Papers

10:00

ET4 1 New Adventure in Gaseous Positronics - A Cryogenic Beam*
C.M. SURKO,† *University of California, San Diego*

Buffer-gas-trap based beams have proven a reliable workhorse to study positron scattering and annihilation [1]. The state of the art beam has a total energy spread ~ 40 meV FWHM using 300 K gas. Described here is work to create beams with narrower energy spreads (goal: total spread $\leqslant$ 5 meV FWHM using 50 K buffer gas). A Born-approximation model is used to describe cooling on vibrational and rotational excitations. Positron cooling from 1,200 K to 300 K was studied for CF_4, N_2 and CO to obtain the relevant cross sections (by fits to the model) and then predict cooling to 50 K [2]. Using an additional cryogenic trapping stage, positrons have now been cooled to 50 K on N_2 and CO. Since the beam is generated in a magnetic field, the total energy spread is characterized by spreads parallel and perpendicular to the field [3]. While the perpendicular temperature is 4 meV (i.e., kT at 50 K), the parallel energy spread is larger. The currently projected total spread is $\leqslant$ 10 meV FWHM - a factor of four better than the 300 K result. Work is in progress to reach the predicted total spread at 50 K of 5 meV FWHM.

*Work supported by NSF grant PHY 1401794.
†In collaboration with M. R. Natisin and J. R. Danielson.

[1] J. R. Danielson *et al.*, Rev. Mod. Phys. **87**, 247 (2015).
[2] M. R. Natisin *et al.*, J. Phys. B **47**, 225209 (2014).
[3] M. R. Natisin *et al.*, Phys. Plasmas **22**, 033501 (2014).

10:30

ET4 2 Positron scattering measurements for application to medical physics
JAMES SULLIVAN, *Australian National University*

While the use of positrons in medical imaging is now well established, there is still much to learn regarding the transport of positrons through the body, and the subsequent damage induced. Current models of dosimetry use only a crude approximation of the collision physics involved, and at low energies misrepresent the thermalisation process to a considerable degree. Recently, collaborative work has commenced to attempt to refine these models, incorporating a better representation of the underlying physics and trying to gain a better understanding of the damage done after the emission of a positron from a medical radioisotope. This problem is being attacked from several different angles, with new models being developed based upon established techniques in plasma and swarm physics. For all these models, a realistic representation of the collision processes of positrons with relevant molecular species is required. At the Australian National University, we have undertaken a program of measurements of positron scattering from a range of molecules that are important in biological systems, with a focus on analogs to DNA. This talk will present measurements of positron scattering from a range of these molecules, as well as describing the experimental techniques employed to make such measurements. Targets have been measured that are both liquid and solid at room temperature, and new approaches have been developed to get absolute cross section data. The application of the data to various models of positron thermalisation will also be described.

Contributed Papers

11:00

ET4 3 Measurement of the Ion Distribution Function in a Dual Frequency Plasma Etch Tool* WALTER GEKELMAN, NATHANIEL MOORE, PATRICK PRIBYL, *Dept of Physics, University of California Los Angeles* MARK KUSHNER, *University of Michigan EECE* The ion energy distribution function, (IEDF) was measured in detail in an industrial etch tool. The plasma was made with an ICP source (440 kHz, 500 W) and two independently controlled bias sources. The Si wafer was placed on a ceramic electrostatic chuck with an embedded capacitor plate. The first source ran at 2.2 MHz (600 Vpp and 2500 W) with a maximum sheath potential drop of 650 V or 2000V. The second source ran at 19 MHz with Vpp of 600 V. The principal diagnostic was Laser Induced Fluorescence on Argon using 611.49 nm light from a tunable dye laser with ions responding to Doppler shifted light. Using cylindrical lens combinations the laser light was transformed into a sheet 15 cm wide and 0.5 cm thick. The beam could be transverse or parallel to the normal of the wafer. The glowing ions (at 461 nm) were photographed by a CCD camera with 400 micron resolution. The laser was phase locked to the 2.2 MHz rf and the IDDF measured as a function of radial position, height above the wafer and at 8 phases. With Vpp = 600 V the highest energy ions observed were 500 eV, 1.2 mm above the wafer. These observations as well as the angular distribution agreed well with a computer simulation. In the dual frequency case when the potential of the wafer was most negative wrt the bulk plasma the IEDF structure 0.8 mm above the wafer was well fitted by 4 Gaussians. The ion flux to the wafer was far more uniform in the dual frequency case.

*This research supported by the NSF and DOE.

11:15

ET4 4 Ab-initio calculations of state-to-state rate coefficients for electron- and atom-molecule scattering at high temperatures VINCENZO LAPORTA, *Ohio Aerospace Institute, Dayton 45431, Ohio* ROBERTO CELIBERTO, *Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica, Politecnico di Bari, Italy* FABRIZIO ESPOSITO, *Istituto di Nanotecnologia, CNR, 70126 Bari, Italy* ESWAR JOSYULA, *Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton 45433, Ohio* In the contribution to conference theoretical calculations of state-by-state rate coefficients for electron-molecule and atom-molecule scattering, by using ab-initio methods, will be presented. In particular nitrogen- and oxygen-involving chemical reactions will be considered. These quantities are of primary importance to study the energy exchange and to implement kinetic models in thermal and chemical non-equilibrium high-temperature aerothermodynamics.

11:30

ET4 5 Expression of a momentum-transfer scattering at an inelastic collision on electron transport in a collisional plasma TOSHIAKI MAKABE, *Keio University* An expression for the inelastic momentum-transfer scattering on the collision integral of the Boltzmann equation is derived in order to reflect the effect of the inelastic collision of an electron with a molecule on the electron kinetics in gases and collisional plasmas. To our knowledge, this is the first attempt to formulate the effect of the momentum-transfer scattering of an inelastic collision. The present procedure is a traditional one in which the Boltzmann equation of electrons is expanded by the Spherical-harmonics in velocity space. It is shown that the effect of the inelastic momentum-transfer on the electron transport is expressed only when we consider the first anisotropic part of the velocity distribution in the expanded Boltzmann equation. In addition, case studies are performed by considering the dependence of the scattering angle and the magnitude distribution. The influence of the inelastic momentum-transfer scattering on the electron transport should be further investigated, particularly in the case of a Ramsauer gas having the relation $Q_{vib}(v) > Q_m(v)$ in the vicinity of the Ramsauer-minimum in SiH_4, CH_4, and CF_4 etc.

11:45

ET4 6 Electron Impact Ionization Cross Sections and Rate Coefficients for Single Carbon Freon Molecules* SATYENDRA PAL, NEERAJ KUMAR, *Department of Physics, MMH College, Ghaziabad, U.P., India* Single carbon Freon molecules or chlorofluorocarbons (CFCs) are important industrial material with wide-ranging applications as refrigerant, aerosol propellant and semiconductor etchant, etc. The large-scale industrial consumption is of particular environmental concern because of its potential for ozone destruction in the stratosphere. In the present work, we have extended and generalized the modified Jain-Khare (JK) semi-empirical formalism for the evaluation of the total ionization cross sections corresponding to the formation of the cations in the electron impact ionization of molecules to the electron impact ionization of single carbon freon molecules, viz. $CFCl_3$, CF_2Cl_2 and CF_3Cl. The integral partial and the total ionization cross sections as function of incident electron energy are evaluated in the energy range varying from ionization threshold to 1000 eV. In absence of available differential cross sections, the corresponding derived partial and total ionization cross sections revealed a reasonably good agreement with the experimental and theoretical data, wherever available. In addition to the differential and integral ionization cross sections, we have also calculated the ionization rate coefficients using the evaluated partial ionization cross sections and the Maxwell-Boltzmann distribution as a function of electron temperature/energy.

*The work is supported by DST, New Delhi, India.

SESSION FT1: PLASMA MEDICINE

Tuesday Afternoon, 13 October 2015; Room: 301 B at 13:30; Masaru Hori, Nagoya University, presiding

Invited Papers

13:30

FT1 1 Cold Atmospheric Plasma for Medicine: State of Research and Clinical Application

THOMAS VON WOEDTKE, *Leibniz Institute for Plasma Science and Technology (INP Greifswald)*

Basic research in plasma medicine has made excellent progress and resulted in the fundamental insights that biological effects of cold atmospheric plasmas (CAP) are significantly caused by changes of the liquid environment of cells, and are dominated by redox-active species. First CAP sources are CE-certified as medical devices. Main focus of plasma application is on wound healing and treatment of infective skin diseases. Clinical applications in this field confirm the supportive effect of cold plasma treatment in acceleration of healing of chronic wounds above all in cases where conventional treatment fails. Cancer treatment is another actual and emerging field of CAP application. The ability of CAP to kill cancer cells by induction of apoptosis has been proved in vitro. First clinical applications of CAP in palliative care of cancer are realized. In collaboration with Hans-Robert Metelmann, University Medicine Greifswald; Helmut Uhlemann, Klinikum Altenburger Land GmbH Altenburg; Anke Schmidt and Kai Masur, Leibniz Institute for Plasma Science and Technology (INP Greifswald); Renate Schönebeck, Neoplas Tools GmbH Greifswald; and Klaus-Dieter Weltmann, Leibniz Institute for Plasma Science and Technology (INP Greifswald).

Contributed Papers

14:00

FT1 2 DNA damage in oral cancer and normal cells induced by nitrogen atmospheric pressure plasma jets* XU HAN, JAMES KAPALDO, YUEYING LIU, M. SHARON STACK, SYLWIA PTASINSKA, *University of Notre Dame* Nitrogen atmospheric pressure plasma jets (APPJs) have been shown to effectively induce DNA double strand breaks in SCC25 oral cancer cells. The APPJ source constructed in our laboratory operates based on dielectric barrier discharge. It consists of two copper electrodes alternatively wrapping around a fused silica tube with nitrogen as a feed gas. It is generally more challenging to ignite plasma in N2 atmosphere than in noble gases. However, N2 provides additional advantages such as lower costs compared to noble gases, thus this design can be beneficial for the future long-term clinical use. To compare the effects of plasma on cancer cells (SCC25) and normal cells (OKF), the cells from both types were treated at the same experimental condition for various treatment times. The effective area with different damage levels after the treatment was visualized as 3D maps. The delayed damage effects were also explored by varying the incubation times after the treatment. All of these studies are critical for a better understanding of the damage responses of cellular systems exposed to the plasma radiation, thus are useful for the development of the advanced plasma cancer therapy.

*The research described herein was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Basic Energy Sciences, Office of Science, United States Department of Energy through Grant No. DE-FC02-04ER15533.

14:15

FT1 3 Plasma treatment of onychomycosis ZILAN XIONG, *University of California at Berkeley, Berkeley, CA 94720, USA* JEFF ROE, TIM GRAMMER, *DeviceFarm, Newark, CA 94560, USA* YEON-HO HIM, *Chonbuk National University, 561-756, Korea* DAVID B. GRAVES, *University of California at Berkeley, Berkeley, CA 94720, USA* GRAVES LAB, DEPARTMENT OF CHEMICAL AND BIOMOLECULAR ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY TEAM, DEVICEFARM, NEWARK, CA 94560, USA COLLABORATION Onychomycosis or fungal infection of the toenail or fingernail is a common affliction. Approximately 10% of the world's adult population is estimated to suffer from onychomycosis. Current treatment options such as topical creams, oral drugs, or laser treatments are generally limited by a variety of problems. We present results for an alternative onychomycosis treatment scheme using atmospheric pressure cold air plasmas. Using thinned cow hoof as a model nail material, we tested the ability of various plasma sources to act through the model nail to eradicate either bacteria or fungus deposited on the opposite side. Following 20 minute exposure to a surface microdischarge (SMD) device operating in room air, we observed a ~ 2 log reduction of E. coli. A similar result was obtained against T. rubrum after 45 min plasma treatment. NOx species concentration penetrating through the model nail as well as uptake into the nail were measured as a function of nail thickness. We propose that these plasma-generated species, or perhaps their reaction products, are responsible for at least part of the observed anti-microbial effect. We also explore the use of ultraviolet light acting in synergy with plasma-generated chemical species.

14:30

FT1 4 Responses of cells in plasma-activated medium HIROMASA TANAKA, MASAAKI MIZUNO, KENJI ISHIKAWA, KEIGO TAKEDA, HIROSHI HASHIZUME, KAE NAKAMURA, HIROAKI KAJIYAMA, *Nagoya University* HIROYUKI KANO, *NU Eco Engineering* YASUMASA OKAZAKI, SHINYA TOYOKUNI, SHOICHI MARUYAMA, YASUHIRO KODERA, HIROKO TERASAKI, *Nagoya University* TETSUO ADACHI, *Gifu Pharmaceutical University* MASASHI KATO, FUMITAKA KIKKAWA, MASARU HORI, *Nagoya University* Plasma consists of electrons, ions, radicals, and lights, and produces various reactive species in gas and liquid phase. Cells receive various inputs from their circumstances, and induce several physiological outputs. Our goal is to clarify the relationships between plasma inputs and physiological outputs. Plasma-activated medium (PAM) is a circumstance that plasma provides cells and our previous studies suggest that PAM is a promising tool for cancer therapy. However, the mode of actions remains to be elucidated. We propose survival and proliferation signaling networks as well as redox signaling networks are key factors to understand cellular responses of PAM-treated glioblastoma cells.

14:45

FT1 5 Effect of microplasma irradiation on skin barrier function KAZUO SHIMIZU, *Organization for Innovation and Social Collaboration, Shizuoka University* NHAT AN TRAN, *Graduate school of engineering Shizuoka University* MARIUS BLAJAN, *Organization for Innovation and Social Collaboration, Shizuoka University* This study investigates the feasibility of atmospheric-pressure argon microplasma irradiation (AAMI) to promote drug delivery through skin. Yucatan micropig skin was used as a biological object for evaluation of in vitro percutaneous absorption. The changes in lipids, proteins and water content of the pig stratum corneum (SC) after AAMI were compared to those of a tape stripping test (TST) and plasma jet irradiation (PJI) using attenuated total reflection-Fourier transform infrared spectroscopy analysis. The significant reduction in the methylene stretching modes absorbance resulted in the disturbance in the SC lipids caused by AAMI was observed at 2850 and 2920 cm^{-1}. Moreover, as the result of TST, trans-epidermal water loss (TEWL) after both AAMI and PJI were also increased, that could lead to a decrease of barrier function of SC, and could enhance the transdermal absorption of drugs. Under the conditions of this study, TEWL value of 5 minutes AAMI (35.92 ± 3.48 g/m^2h) was approximately the same as that value of 10 times TST (34.30 ± 3.54 g/m^2h), that makes the effect of these manipulations on the surfaces is considered to be at the same levels. Furthermore, unlike the obtained microscopic observation from PJI, there was no thermal damage observed on the skins after AAMI.

15:00

FT1 6 Investigation of selective induction of breast cancer cells to death with treatment of plasma-activated medium* HIROSHI HASHIZUME, HIROMASA TANAKA, KAE NAKAMURA, *Nagoya University* HIROYUKI KANO, *NU EcoEngineering Co., Ltd.* KENJI ISHIKAWA, FUMITAKA KIKKAWA, MASAAKI MIZUNO, MASARU HORI, *Nagoya University* The applications of plasma in medicine have much attention. We previously showed that plasma-activated medium (PAM) induced glioblastoma cells to apoptosis. However, it has not been elucidated the selectivity of PAM in detail. In this study, we investigated the selective effect of PAM on the death of human breast normal and cancer cells, MCF10A and MCF7, respectively, and observed the selective death with fluorescent microscopy. For the investigation of cell viability with PAM treatment, we prepared various PAMs according to the strengths, and treated each of cells with PAMs. Week PAM treatment only decreased the viability of MCF7 cells, while strong PAM treatment significantly affected both viabilities of MCF7 and MCF10A cells. For the fluorescent observation, we prepared the mixture of MCF7 and fluorescent-probed MCF10A cells, and seeded them. After the treatment of PAMs, the images showed that only MCF7 cells damaged in the mixture with week PAM treatment. These results suggested that a specific range existed with the selective effect in the strength of PAM.

*This work was partly supported by a Grant-in-Aid for Scientific Research on Innovative Areas "Plasma Medical Innovation" Grant No. 24108002 and 24108008 from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

15:15

FT1 7 Antitumor effect of synergistic contribution of nitrite and hydrogen peroxide in the plasma activated medium NAOYUKI KURAKE, HIROMASA TANAKA, KENJI ISHIKAWA, KAE NAKAMURA, HIROAKI KAJIYAMA, FUMIAKI KIKKAWA, *Nagoya University* TAKASHI KONDO, *Toyama University* MASAAKI MIZUNO, KEIGO TAKEDA, HIROKI KONDO, MAKOTO SEKINE, MASARU HORI, *Nagoya University* Non-equilibrium atmospheric pressure plasmas (NEAPP) have been attracted attention in the noble application of cancer therapy. Although good effects of the Plasma-Activated-Medium (PAM) such as the selective antitumor effect and killing effect for the anticancer agent resistant cells were reported, a mechanism of this effect has not been still clarified yet. In this study, we have investigated a contribution of the reactive nitrogen and oxygen species (RNOS) generated in PAM such as hydrogen peroxide and nitrite. Those species generated in the PAM quantitatively measured by light absorbance of commercial regent. Moreover, viable cell count after cell culture with those RNOS intentionally added medium or PAM were also measured by MTS assay. Our NEAPP source generated hydrogen peroxide and nitrite with the generation ratio of 0.35 μM/s and 9.8 μM/s. In those RNOS, hydrogen peroxide has respective antitumor effect. On the other hands, nitrite has no antitumor effect singly. But, synergistically enhance the antitumor effect of hydrogen peroxide. Moreover, this effect of those RNOS also contribute for the selectively cancer killing effect of PAM.

SESSION FT2: INDUCTIVELY COUPLED PLASMAS

Tuesday Afternoon, 13 October 2015
Room: 308 AB at 13:30
Earl Scime, West Virginia University, presiding

Contributed Papers

13:30

FT2 1 Student Award Finalist: Negative Power Absorption in Low-Pressure Inductive Discharges JAN TRIESCHMANN, MARTIN LAPKE, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Bochum, Germany* Inductively coupled radio-frequency plasmas for technological applications are frequently operated at relatively low gas pressures (below 10 Pa). One specific feature of this regime is that collisions of electrons with atoms or molecules of the neutral background gas are infrequent. Under these conditions the discharges are operated in the nonlocal regime, i.e., the relation between the high frequency current density and the electric field is nonlocal. To describe this specific situation, Maxwell's equations have to be coupled self-consistently to Boltzmann's equation. In this paper we present an analytical, self-consistent solution to the one-dimensional problem of a plane wave propagating from one half-space (vacuum) into the other filled with a bounded homogeneous plasma. We particularly discuss the anomalous skin effect, negative power absorption, and phase mixing. The results from the analytical model are finally compared with results from self-consistent Particle-In-Cell simulations.

13:45

FT2 2 3D-PIC simulation of an inductively coupled ion source* ROBERT HENRICH, NINA SARAH MUEHLICH, MICHAEL BECKER, CHRISTIAN HEILIGER, *Justus-Liebig-University Giessen, Institut fuer Theoretische Physik* Inductively coupled ion sources are applied to a wide range of plasma applications, especially surface modifications. The knowledge of the behavior and precise information of the plasma parameters are of main importance. These values are tedious to measure without influencing the discharge. By applying our fully three-dimensional PlasmaPIC tool we are able to reach these plasma parameters with a spatial and temporal resolution which is quite hard to achieve experimentally. PlasmaPIC is used for modeling discharges in arbitrary geometries without limitations to any symmetry. By this means we are able to demonstrate that the plasma density has an irrotational character. Furthermore, we will show the dependence of the plasma parameters of different working conditions. We will show that for gridded inductively coupled ion sources the neutral gas pressure inside the discharge chamber depends on the extraction of ions. This effect is considered in PlasmaPIC by a self-consistent coupling of the neutral gas simulation and the plasma simulation whereas the neutral gas distribution is calculated using the direct simulation Monte Carlo method (DSMC).

*This work has been supported by the "Bundesministerium fuer Wirtschaft und Energie." Grant 50RS1507.

14:00

FT2 3 Vibrational kinetics in Cl_2 and O_2 low-pressure inductively-coupled plasmas* JEAN-PAUL BOOTH, MICKAEL FOUCHER, DANIIL MARINOV, PASCAL CHABERT, *LPP-CNRS, Ecole Polytechnique, Palaiseau, France* ANNA ANNUSOVA, VASCO GUERRA, *IPFN, IST, Universidade de Lisboa, Portugal* ANKUR AGARWAL, SHAHID RAUF, *Applied Materials, Sunnyvale, CA* Low energy electron interactions with molecules via resonances can cause vibrational excitation (affecting chemical kinetics), electron energy loss and modification of the EEDF. However, with the exception of N_2 and H_2 plasmas, very little attention has been paid to this subject. We have implemented a novel high-sensitivity ultra-broadband UV absorption bench, allowing spectra to be recorded with noise as low as 2×10^{-5} over a 250 nm wavelength range, and recording of complete vibronic bands. We applied this to radiofrequency inductively-coupled plasmas in low pressure (5-50 mTorr) pure O_2 and pure Cl_2. In O_2 plasmas we surprisingly observe highly vibrationally excited O_2 (v″ up to 18) via B-X Schumann-Runge bands. Cl_2 molecules show a broad UV absorption spectrum in the region 250-400 nm, with distinctly different absorption spectra for vibrationally excited molecules. However, only a small fraction of the Cl_2 molecules were observed in vibrationally excited states and the vibrational temperature is close to equilibrium with the local gas translational temperature (up to 1000 K), in contrast to O_2. We are currently working on global models with vibrational kinetics to explain these results.

*Work supported by LABEX Plas@par (ANR-11-IDEX-0004-02), and Applied Materials.

14:15

FT2 4 Characterization of Inductively Coupled Plasmas in High Power, High Pressure Regime JUN-CHIEH WANG, JASON

TUESDAY AFTERNOON \ FT2

KENNEY, ANKUR AGARWAL, MICHAEL NICHOLS, JAMES ROGERS, SHAHID RAUF, *Applied Materials, Inc* Inductively coupled plasmas (ICP) are widely used in the microelectronic industry for thin film etching. ICPs have typically been operated at low gas pressures (<50 mTorr) and they have been well-characterized in this regime. Several applications requiring high etch rates (e.g., vertical NAND etch) have recently extended the use of ICPs to the high power (>4000 W) and high pressure (>100 mTorr) regime. ICP operation in this high-power, high-pressure regime imposes a tremendous challenge of achieving good plasma uniformity over large substrates. This necessitates a good theoretical understanding of the underlying physics, thorough experimental characterization, and more accurate numerical models for hardware design guidance. In this study, we will focus on the characterization of ICP in the high-power, high-pressure regime. Computational modeling is done using CRTRS, our in-house 2D/3D plasma model. The fluid plasma model is coupled to a circuit model to self-consistently account for the capacitive coupling from the coils that is expected to dominate in this operating regime. Properties of Ar plasma will be discussed and compared with experiments. The impact of critical operating parameters such as ICP power, pressure, flow rate, and current ratio (in multi-coil antenna structures) on plasma characteristics will be examined. Results in relevant processing gases will also be discussed.

14:30

FT2 5 Ignition Delay in a Pulsed Inductively Coupled Plasma (ICP) in Tandem with an Auxiliary ICP VINCENT M. DONNELLY, LEI LIU, SHYAM SRIDHAR, DEMETRE J. ECONOMOU, *University of Houston* Plasma ignition delays were observed in a "main" ICP, in tandem with an "auxiliary" ICP. The Faraday-shielded ICPs were separated by a grounded metal grid. Power (13.56 MHz) to the main ICP was pulsed with a frequency of 1 kHz, while the auxiliary ICP was operated in continuous wave (cw) mode. In chlorine plasmas, ignition delay was observed for duty cycles greater than 60% and, in contrast to expectation, the delay was longer with increasing duty cycle up to $\sim 99.5\%$. The ignition delay could be manipulated by changing the auxiliary and/or main ICP power. Langmuir probe measurements provided the temporal evolution of electron temperature, and electron and positive ion (n_+) densities. These measurements revealed that the plasma was re-ignited shortly after the decaying n_+ in the main ICP reached the density ($n_{+,aux}$) measured when only the auxiliary ICP was powered. At that time, the depressed electron density increased sharply resulting in plasma re-ignition. Plasma ignition delay occurred when the afterglow of the pulsed plasma was not long enough for n_+ to reach $n_{+,aux}$ during the afterglow. Besides Cl_2, plasma ignition delays were also observed in other electronegative gases (SF_6, CF_4/O_2 and O_2) but not in an electropositive gas (Ar).

14:45

FT2 6 Producing ion waves from acoustic pressure waves in pulsed ICP: Modeling vs. Experiments EMILIE DESPIAU-PUJO, GILLES CUNGE, MAXIME DARNON, NADER SADEGHI, *CNRS/Univ. Grenoble Alpes/CEA, LTM* NICHOLAS BRAITHWAITE, *Open University* Neutral depletion is an important phenomenon in CW high-density plasmas, mostly caused by gas heating - with a small contribution due to electron pressure Pe - under typical material processing conditions. In pulsed ICP, neutral depletion plays an important role on radical transport in the afterglow. At the beginning of the afterglow, Pe drops rapidly (10μs) by electron cooling and the gas cools down as well. It generates a neutral pressure gradient between the plasma bulk and the reactor walls, which in turn forces the cold surrounding gas to move rapidly towards the center, thus launching an acoustic wave in the reactor. Fast gas displacement is evidenced by measuring Al atoms drift velocity in the early afterglow of a Cl2/Ar discharge by time-resolved LIF, the acoustic wave in the chamber being observed by mass spectrometry. 2D fluid simulations of Cl2 pulsed ICP predict similar results. These phenomena are further studied during both the plasma ignition and afterglow using modeling and experiments. Strong oscillations are observed both on the Cl2 neutral densities and on the ion flux. As neutrals are pushed towards (or outwards) the chamber walls by the pressure gradient, ions are also pushed in that direction through collisions, as well captured by our ion flux probe.

15:00

FT2 7 Electronegative Plasma Instabilities in Pulsed Plasmas* PATRICK PRIBYL, WALTER GEKELMAN, *Dept. Physics University of California, Los Angeles* Modern inductively coupled plasma reactors can all be operated in unstable configurations, although in many cases normal precautions result in quiescent stable operation. However, electronegative gases that are important for etch processes have a series of instabilities that occur at process relevant conditions. These have been studied since the 1990s, but are becoming a much more important today as plasma reactors are being pushed to produce ever finer features, and tight control of the etch process is becoming crucial. A device at UCLA was designed to simulate industrial reactors used in semiconductor processing. Various gas mixtures are programmable (Ar, SF6, O2). ICP coils in different configurations are driven by pulsed RF generators operating separately from 400 kHz to 40 MHz. A stainless steel "chuck" assembly can be positioned at a variable height, either with a wafer and RF bias, or with direct DC bias to directly program sheath voltage. A computer controlled automated probe drive can access the entire volume above the substrate. The probe can be a Langmuir probe, a "Bdot" probe, or an emissive probe the latter used for more accurate determination of plasma potential. A microwave interferometer is available to measure line-averaged electron density. Optical emission can be diagnosed using a half or 1 meter spectrometer. We describe work with electronegative gases to characterize and potentially stabilize the plasma against ionization instabilities using pulsed plasmas.

*Work supported by NSF and done at the Basic Plasma Science Facility.

15:15

FT2 8 Characterization of inductively coupled Ar and Ar/CH4 plasma using tuned single Langmuir probe and fluid simulation JU-HONG CHA, MOON-KI HAN, KWON-SANG SEO, DONG-HYUN KIM, HAE JUNE LEE, HO-JUN LEE, *Department of Electrical and Computer Engineering, Pusan National University* An inductively coupled plasma source driven by 13.56 MHz was prepared for the deposition of a-C:H and hydro-fluorocarbon thin film. Properties of the plasma source are investigated by fluid simulation including Navier-Stokes equations and home-made tuned single Langmuir probe. Signal attenuation ratios of the Langmuir probe at first and second harmonic frequency were 49dB and 46dB respectively. Dependencies of plasma parameters on process parameters were well agreed with simulation results. It was found that gas flow field significantly affect spatial distribution of electron density and temperature even in inert gas feeding case. Higher electron density and lower temperature was observed near the gas inlet area. Ar/CH4 plasma simulation results shown that hydrocarbon radical densities have their lowest value at the vicinity of gas feeding line due to high flow velocity. For input power density of 0.07 W/cm^3, CH radical density follows electron density distribution. On the other hand, central region of the chamber become deficient in CH3 radical due to high dissociation rate accompanied with high electron density. The result suggest that optimization of discharge power is important for controlling deposition film quality in high density plasma sources.

SESSION FT3: MICROPLASMAS

Tuesday Afternoon, 13 October 2015; Room: 305 AB at 13:30; Laxminarayan Raja, presiding

Invited Papers

13:30

FT3 1 Spots and patterns on electrodes of gas discharges*

MIKHAIL BENILOV, *Departamento de Física, CCCEE, Universidade da Madeira and Instituto de Plasmas e Fusão Nuclear, IST, Universidade de Lisboa, Portugal*

Concentration of electrical current onto the surface of electrodes of gas discharges in well-defined regions, or current spots, is often the rule rather than the exception. These spots occur on otherwise uniform electrode surfaces, a regime where one might expect a uniform distribution of current over the surface. In many cases, multiple spots may appear, forming beautiful patterns and surprising the observer. Important advances have been attained in the last 15 years in experimental investigation, understanding, and modelling of spots and patterns in discharges of different types, in particular, high-pressure arc discharges, dc glow discharges, and barrier discharges. It became clear that in many, if not most, cases there is no need to look for special physical mechanisms responsible for the formation of spots or patterns on uniform electrode surfaces: the spots or patterns originate in self-organization caused by (nonlinear) interaction of well-known mechanisms. In particular, standard mechanisms of near-cathode space-charge sheath are sufficient to produce self-organization, and it is this kind of self-organization that gives rise to cathode spots in low-current high-pressure arcs and normal spots and patterns of spots on cathodes of dc glow discharges. It was shown that spots and patterns on electrodes of gas discharges, being self-organization phenomena, are inherently related to multiple solutions, with one of the solutions describing a mode with a uniform distribution of current over the electrode surface and the others describing regimes with different spot patterns. These multiple solutions exist even in the most basic self-consistent models of gas discharges. In particular, multiple solutions have been found for dc glow discharges; the fact rather surprising by itself, given that such discharges have been under intensive theoretical investigation for many years. A concise review of the above-described advances is given in this talk.

*Work supported by FCT of Portugal through the projects PTDC/FIS-PLA/2708/2012 and Pest-OE/UID/FIS/50010/2013.

Contributed Papers

14:00

FT3 2 Modeling of Microplasmas with Nano-Engineered Electrodes SERGEY MACHERET, SIVA SHASHANK THOLETI, ALINA ALEXEENKO, *Purdue University* Microplasmas can potentially be used as unique tunable dielectrics for reconfigurable radio-frequency systems, if electron densities of 10^{10}-10^{12} cm^{-3} can be sustained in cavities smaller than 100 micron. However, for low loss tangent, gas pressures below 10 mTorr would be required, whereas the physics of electron impact ionization dictates the pd scaling so that microplasmas must operate at high gas pressures, hundreds of Torr, and also high voltages. We analyze a new principle of plasma generation that goes well beyond the pd scaling by eliminating electron impact ionization. In the new concept, electrons are generated at the cathode by field emission from nanotubes, and ions are independently produced in field ionization at atomically-sharp tips on the anode. The electrons and ions then move in the opposite directions, mix, and create a plasma. The low pressure results in collisionless motion with no electron-impact ionization. One-dimensional PIC/MCC calculations show that emitters such as carbon nanotubes placed sparsely on the cathode, combined with field ionization nanorods at the anode, can indeed ensure steady-state electron densities of up to 10^{12} cm^{-3} at gas pressure lower than 10 mTorr with only 50-100 Volts applied cross a 40-50 μm gap.

14:15

FT3 3 Breakdown phenomenon across micrometer-scale surface gap under positive impulse voltage HIROYUKI IWABUCHI, SHIGEYASU MATSUOKA, AKIKO KUMADA, KUNIHIKO HIDAKA, *The University of Tokyo* With the miniaturization of electronic devices, insulation width between electrodes have been accordingly reduced. Consequently, electrical breakdown phenomenon across micrometer-scale gap is of great practical interest for insulation designing of miniaturized devices. In this research, breakdown characteristics across micrometer-scale surface gap were observed under the application of positive impulse voltage. As a result, breakdown voltage under positive impulse voltage across surface gap was independent of gap width. The results indicate that initial electrons emitted from the surface of the insulator in the vicinity of anode. In order to investigate the breakdown process, particle-in-cell simulation based on monte-carlo method was also conducted. Considering electron emission from the surface of the insulator, electrons emitted from the insulator surface can collide to the neutral particles and positive ions are generated. Generated ions move into the insulator surface and the secondary electrons are emitted. Consequently, discharge path along the surface of the insulator is formed. The results show that electron emission from the surface of the insulator plays an important role in breakdown across micrometer-scale surface gap.

14:30

FT3 4 Operating modes of field emission assisted microplasmas in the microwave regime ARGHAVAN ALAMATSAZ, AYYASWAMY VENKATTRAMAN, *University of California, Merced* Field-induced electron emission from the cathode and its interaction with microdischarges has gained significant attention in the last few years particularly in the context of microscale gas breakdown. Recent advances in nanofabrication have led to the development of novel cathodes that demonstrate impressive field emission properties with turn-on fields as low as 1 V/μm and field enhancement factors as high as 1000 implying that field emission could play an important role in microplasmas as large as 500 μm. Recent studies on direct current microplasmas have shown that field emission triggers the transition from an abnormal glow mode to an arc-like mode with negative differential resistance. This talk will extend the results obtained for DC field emission assisted (FEA) microplasmas to the high frequency regime with specific emphasis on radio frequency and microwave excitations. Particle-in-cell with Monte Carlo collisions (PIC-MCC) simulations are used to determine the current-voltage characteristics and microplasma properties including number density, electron temperature, electron energy distribution function and power density. Apart from quantifying the influence of excitation frequency, the role of field emission on transition to γ-modewill also be discussed.

14:45

FT3 5 Optical emission spectroscopy of nanosecond repetitively pulsed microplasmas generated in air at atmospheric pressure THOMAS ORRIERE, ERIC MOREAU, NICOLAS BENARD, DAVID PAI, *Institut PPRIME* Nanosecond repetitively pulsed (NRP) microplasmas are generated in room temperature air at atmospheric pressure, in order to investigate the enhanced control of discharge properties via the combined effects of spatial confinement and nanosecond repetitive pulsing. Discharges were generated using high-voltage pulses of 15-ns duration applied to a tungsten pin-to-pin reactor, with inter-electrode gap distances (d) from 2 mm down to 0.2 mm. Optical emission spectroscopy and electrical characterization performed on the discharge indicate that heat transfer and plasma chemistry are influenced by the microplasma geometry. Ultrafast gas heating is observed upon deducing the rotational temperature of N_2 from the measured emission spectrum of the N_2 ($C\rightarrow B$) (0, 2) and (1, 3) transition bands, but use of the microplasma geometry ($d = 0.2$ mm) results in lower gas temperatures than in larger discharge gaps ($d = 2$ mm), including at high pulse repetition frequency (30 kHz) where substantial steady-state gas heating can occur. The measured Stark broadening of the H_α transition is significantly greater than for previously studied NRP discharges in air at atmospheric pressure, indicating that the maximum electron number density may be correspondingly much greater, up to 10^{18} cm^{-3}. Furthermore, for NRP microplasmas, the intensities of emission from excited atomic ions (O^+ and N^+) are much higher than those of excited neutral atoms (O and N), in contrast to NRP discharges generated in larger discharge gaps.

15:00

FT3 6 Suppression of Instability of High Pressure DC Microplasma Operating in the Negative Differential Resistance (NDR) Regime* RAJIB MAHAMUD, TANVIR I. FAROUK, *University of South Carolina* Microplasma devices have been the subject of considerable interest and research during the last decade. In a DC system most of the operation regime of the plasma discharges studied fall in the "abnormal," "normal" and "corona" modes - where a quasi-steady state is achieved. It is well known that even in a DC system the negative differential resistance (NDR) regime can trigger self pulsing discharges. These pulsations are initiated by the parasitic capacitance of the system hence governed by the response time of the power circuit. The circuit response time is required to be larger than the ion transit time to initiate the oscillations. In this present study a suppressor circuit element in the form of an inductor is used to restrain the plasma from switching to a self pulsing mode. It has been identified that the combined response time of the inductor and the plasma discharge (L/Rplasma) has to be larger than the power circuit time constant (RC) to achieve suppression. Inhibition of oscillation has been observed in both experiments and numerical simulations. The obtained voltage-current characteristics show that the inductor element extends the normal glow regime to lower current. Additional parametric simulations are conducted to map out a "stable" operation regime.

*The author would like to thank DARPA (ARO Grant No. W911NF1210007) and University of South Carolina (USC) for the financial support of the work.

15:15

FT3 7 Plasma Tunable LC Resonator for High-Power Electromagnetic Applications ABBAS SEMNANI, SERGEY MACHERET, DIMITRIOS PEROULIS, *Purdue University* High-power tunable filters are in high demand in transmitters found in radars and many communication systems such as satellite and broadcasting stations. Limited power handling renders most semiconductor technologies inherently suboptimal options for these systems. Therefore, mechanically-tunable cavity-based filters are often employed in such cases, resulting in bulky, slow, and heavy systems. In this work, we study the application of plasma as an alternative frequency tuning mechanism for high-power applications even in environmentally and/or mechanically harsh conditions. For a given gas type and pressure, the real and imaginary parts of the dielectric permittivity of a plasma can be varied by changing the electron density, which, depending on the discharge regime, can be implemented by changing the discharge current, voltage, or the magnitude of an auxiliary electric field. In this work, a simple LC resonator tuned to several hundred MHz was fabricated and tested. The tunable capacitor of the resonator was implemented by a commercially available gas discharge tube (GDT), a mm-scale plasma device with gas pressure of 100s of mTorr. Measurement results reveal a continuous tuning range of more than 50% when the applied discharge current is increased from zero to 90 mA.

SESSION FT4: THERMAL PLASMAS; MATERIALS APPLICATIONS

Tuesday Afternoon, 13 October 2015; Room: 303 AB at 13:30; Masaya Shigeta, Osaka University, presiding

Invited Papers

13:30

FT4 1 Thermal Plasmas: Influence of Current Modulation on Process Performance*

JOCHEN SCHEIN,[†] *Universitaet der Bundeswehr Muenchen*

Due to the widespread industrial use of thermal plasmas in the field of joining, cutting and the application of coatings new challenges arise owed to the advent of new materials or the drive to reduce cost or improve quality. These challenges may be met by using technological innovations like innovative fast power supplies. In the presence of strong gas flows and a fixed cathodic attachment the anode attachment position is determined by an unstable balance between the drag force on the plasma column exerted by the gas and the Lorentz Force due to the system's magnetic field distribution, leading to a constant arc motion and arc voltage fluctuation. Thus by supplying a sufficiently high and steep current pulse a re-positioning might be initiated by a sudden change of the Lorentz Force thus an externally controlled movement of the arc would be possible. In wire arc spraying a pulsed current is imposed upon the DC supply of the wire arc system. It is observed that steep current increases tend to produce sudden current drops, indicating a jump of the arc. For a certain pulse frequency this pulsing leads to a controlled motion of the arc along the electrode surfaces. Coatings produced with this technology exhibited a lower porosity than DC sprayed coatings and a lower oxide content. In collaboration with Alexander Atzberger and Michal Szulc, Universitaet der Bundeswehr Muenchen; Institute for plasma technology and mathematics (LPT) Neubiberg, Germany.

*This work was supported by AiF (Arbeitsgemeinschaft industrielle Forschung).
†Institute for plasma technology and mathematics (LPT), Neubiberg, Germany.

Contributed Papers

14:00

FT4 2 Fundamental of a Planar Type of Inductively Coupled Thermal Plasma (ICTP) on a Substrate for a Large-area Materials Processings MAIKAI SUANTIAL, MIKA AKAO, HIROMITSU IRIE, YUJI MARUYAMA, YASUNORI TANAKA, YOSHIHIKO UESUGI, TATSUO ISHIJIMA, *Kanazawa University* KANAZAWA UNIVERSITY TEAM In this paper, the fundamental of a planar type Ar inductively coupled thermal plasmas (ICTP) with oxygen molecular gas have been studied on a substrate. Previously, we have developed a planar-ICTP torch with a rectangular quartz vessel with an air core coil or a ferrite core coil instead of a cylindrical tube for a large-area materials processing. For adoption of such a planar-ICTP to material processings, it needs to sustain the ICTP with molecular gases on a substrate stably. To consider the uniformity of the ICTP formed on the substrate, spectroscopic observation was carried out at 3 mm above the substrate. Results showed that the radiation intensities of specified O atomic lines were almost uniformly detected along the surface of the substrate. This means that O excited atoms, which are important radicals for thermal plasma oxidation, are present in planar-ICTP uniformly on the substrate.

14:15

FT4 3 Potential Alternatives for Advanced Energy Material Processing in High Performance Li-ion Batteries (LIBs) via Atmospheric Pressure Plasma Treatment JENQ-GONG DUH, SHANG-I CHUANG, CHUN-KAI LAN, HAO YANG, HSIEN-WEI CHEN, *National Tsing Hua University, Hsinchu, Taiwan* A new processing technique by atmospheric pressure plasma (APP) jet treatment of LIBs was introduced. Ar/N_2 plasma enhanced the high-rate anode performance of $Li_4Ti_5O_{12}$. Oxygen vacancies were discovered and nitrogen doping were achieved by the surface reaction between pristine $Li_4Ti_5O_{12}$ and plasma reactive species (N^* and N_2^+). Electrochemical impedance spectra confirm that plasma modification increases Li ions diffusivity and reduces internal charge-transfer resistance, leading to a superior capacity (132 mAh/g) and excellent stability with negligible capacity decay over 100 cycles under 10C rate. Besides 2D material surface treatment, a specially designed APP generator that are feasible to modify 3D TiO_2 powders is proposed. The rate capacity of 20 min plasma treated TiO_2 exhibited 20% increment. Plasma diagnosis revealed that excited Ar and N_2 was contributed to TiO_2 surface reduction as companied by formation of oxygen vacancy. A higher amount of oxygen vacancy increased the chance for excited nitrogen doped onto surface of TiO_2 particle. These findings promote the understanding of APP on processing anode materials in high performance LIBs.

14:30

FT4 4 Investigation on evaporation of Ti feedstock and formation of precursor TiO molecules during TiO_2 nanopowder synthesis in induction thermal plasma with time-controlled feedstock injection NAOTO KODAMA, KENTARO KITA, YOSUKE ISHISAKA, YASUNORI TANAKA, YOSHIHIKO UESUGI, TATSUO ISHIJIMA, *Kanazawa University* SHIORI SUEYASU, KEITARO NAKAMURA, *Nisshin Seifun Group Inc.* KANAZAWA UNIVERSITY TEAM, NISSHIN SEIFUN GROUP INC. TEAM The method using inductively coupled thermal plasma(ICTP) is very effective for nanopowder(NPs) synthesis. However, NPs formation process in the ICTP torch has not been clarified. In this study, the two-dimensional spectroscopic observation was carried out for ICTP torch during TiO_2 NPs synthesis process with time-controlled feedstock injection. In order to investigate evaporation process of feedstock and formation process of precursor molecules, Ti feedstock was intermittently injected into the ICTP. Ti I(453.32 nm) and TiO(621 nm) were observed by using an imaging spectroscopic system. Observation results show that injected Ti feedstock was evaporated in the ICTP. Then, generated Ti atoms were transported to downstream of the torch by gas flow and were diffused to the radial direction by density gradient. High concentration of TiO molecular gas was formed only around central axis region in the torch.

14:45

FT4 5 Time-dependent areal mass density for disc-shaped substrates in a corona-activated flow stream at atmospheric pressure for argon/acetylene admixture SHUZHENG XIE, ROKIBUL ISLAM, BASHIR HUSSEIN, KARL ENGLUND, PATRICK PEDROW, *Washington State University* In this research we use a 40-needle array energized with 60 Hz AC voltage in the range 5 to 15 kV RMS. Plasma processing takes place downstream from a grounded planar screen (the opposing electrode). The needle-to-screen gap is in the range 4 to 10 cm and its E-field generates weakly ionized plasma via streamers and back corona. Deposited material is plasma-polymerized acetylene. Substrates are potassium bromide, mica, wood, paper, and gold-covered solids. Substrate chemical species influence the efficiency with which the disc amasses plasma-polymerized material, at least until the substrate is fully covered with film. Early plasma-polymerization is accompanied by nucleation-site-dominated nodules but longer term deposition results in a film that fully covers the substrate. We will report on time-dependent areal mass density associated with run times in the range 5-60 minutes. Film thickness will be measured using instruments that include visible light microscopy, TEM, and SEM. Others in our research group are studying areal mass density for early times (1-5 minutes) when nodule growth (at nucleation sites) dominates the deposition process.

15:00

FT4 6 Nitrogen-Doped Ultrananocrystalline Diamond/Hydrogenated Amorphous Carbon Composite Films/p-Silicon heterojunction TSUYOSHI YOSHITAKE, ABDELRAHMAN ZKRIA, *Department of Applied Sciences for Electronics and Materials, Kyushu University* Nitrogen-doped ultrananocrystalline diamond/hydrogenated amorphous carbon composite (UNCD/a-C:H) films were grown by coaxial arc plasma deposition method (CAPD), in ambient of nitrogen and hydrogen mixed gas. Heterojunction structures of n-UNCD/p-Si were prepared by growing n-doped UNCD thin films onto p-type Si (100) substrates. The heterojunction parameters were evaluated based on current–voltage and capacitance–voltage measurements at room temperature. The obtained results introduce the n-UNCD/p-Si heterojunction as a candidate for the electronic device applications

15:15

FT4 7 Ablation and deposition processes in carbon arc discharge for nanosynthesis* YEVGENY RAITSES, JONATHAN NG, *Princeton Plasma Physics Laboratory, Princeton, NJ 08543* VALERIAN NEMCHINSKY, *Keiser University, Fort Lauderdale, FL 33309* YAO-WEN YEH, *Princeton University, Princeton, NJ 08543* SOPHIA GERSHMAN, VLAD VEKSELMAN, *Princeton Plasma Physics Laboratory, Princeton, NJ 08543* The anodic arc discharges with consumed anodes are used to produce various nanoparticles, including carbon nanotubes [1]. Our experiments with the carbon arc at atmospheric pressure helium demonstrate the dependence of the anode ablation rate on the anode diameter, which cannot be explained by changes of the current density at the anode. In particular, the anode ablation rate for narrow graphite anodes is significantly enhanced resulting in high deposition rates of carbonaceous products on the copper cathode [2]. The proposed model explains these results with interconnected steady-state models of the cathode and the anode processes [3]. Results of experimental validation of this model are presented.

*This work was supported by U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division.

[1]C. Journet, W. Maser, P. Bernier, A. Loiseau, *et al.*, Nature **388**, 756 (1997).
[2]J. Ng and Y. Raitses, J. App. Phys. **117**, 063303 (2015).
[3]V. Nemchinskiy and Y. Raitses, J. Phys. D: Appl. Phys. **48**, 245202 (2015).

SESSION GT1: POSTER SESSION I (4:00pm - 6:00 pm)
Tuesday Afternoon, 13 October 2015
Exhibit Exhibit Hall III at 16:00

GT1 1 CHARGED PARTICLE COLLISIONS

GT1 2 Electron Transport in Water Vapour SATORU KAWAGUCHI, KOHKI SATOH, HIDENORI ITOH, *Muroran Institute of Technology* Sets of electron collision cross sections for water vapour previously reported are examined by comparing calculated electron swarm parameters with measured parameters. Further, reliable cross section set of water vapour is estimated by the electron swarm method using Monte Carlo simulation to ensure the accuracy of the swarm parameter calculation. The values of an electron drift velocity, a longitudinal diffusion coefficient, and an effective ionisation coefficient calculated from Yousfi and Benabdessadok's set [1] and those calculated from Itikawa and Mason's set [2] do not necessarily agree with measured data. A new cross section set of water vapour, which consists of three kinds of rotational excitation, two kinds of vibrational excitation, three kinds of electron attachment, twenty-six kinds of electronic excitation, and six kinds of ionisation cross sections, and an elastic collision cross section, is estimated, and an anisotropic electron scattering for elastic and rotational excitation collision is considered. The swarm parameters calculated from the estimated cross section set is in good agreement with measured data in a wide range of reduced electric field.

[1]J. Appl. Phys. **80**, 6619 (1996).
[2]J. Phys. Chem. Ref. Data **34**, 1 (2005).

GT1 3 Low energy electron scattering from atomic oxygen and nitrogen JIM WILLIAMS, *University of Western Australia* Recent considerations of the depth of understanding of laboratory and astrophysical plasmas has drawn attention to theoretical and experimental data for electron collisions with atoms, molecules and ions, particularly for atomic oxygen, nitrogen and carbon atoms [1]. We report accurate experimental differential elastic cross sections from 10 to 150 degrees with energy analysis of the scattered electrons. Phase shifts parameterization [2] of oxygen and nitrogen data enabled calculation of integral elastic and momentum transfer cross sections. Subsequently ionization and excitation processes in nitrogen atoms were explored to see the influence of electronic structure such as the $2s^2\ 2p^3\ {}^2D$ and ${}^2P$ metastable states in the autoionization region [3]. The apparatus used crossed modulated electron and atomic beams with energy selection of the incident electron beam and absolute cross sections determined from experimental parameters using a relative gas flow method.

[1]K. Bartschat and O. Zatsarinny, Phys. Scri. **90**, 054006 (2015).
[2]J. F. Williams and L. J. Allen, J. Phys. B **22**, 3529 (1989).
[3]Y. K. Kim and J. Desclaux, Phys. Rev. A **66**, 012708 (2002).

GT1 4 Electron-impact population transfer rates between metastable and resonance states of argon NADER SADEGHI, *LTM & LIPhy, Univ. Grenoble & CNRS, France* EMILE CARBONE, EDDIE VAN VELDHUIZEN, GERRIT KROESEN, *TUE, Eindhoven, Netherlands* Electron-impact population transfer between metastable and resonance 1s states of argon is studied by time resolved laser pump-probe technique in a surfatron generated argon plasma. A nanosecond laser pulse tuned to a 1s-2p or 1s-3p transition depletes one of the 1s metastable or resonance states of argon and the time variations of the densities in that state and the other three 1s states are then simultaneously monitored by laser absorption diagnostic with different cw diode lasers. Plasma parameters are: 6 mm diameter plasma tube, p = 5-20 mbar, n_e =1-6 * 10^{19} m^{-3}, T_e = 1-2 eV. At such high n_e values e-impact transfers between 1s states dominates over all other loss processes, *i.e.* diffusion, Ar-impact transfers and radiative losses. A simple collisional-radiative model is used to deduce the transfer rates from the time evolution of the densities in the four 1s states following the pulsed laser depletion. At $T_e \geqslant 1.2$ eV, k_{ij} rate coefficients (in units of 10^{19} $m^3.s^{-1}$), for transfers between metastables and neighboring resonance states are $k_{54} = 1.6$ and $k_{32} = 9$, respectively. The population transfer with change of ion-core is weak for $1s_2$ to $1s_5$ ($k_{25} \ll 1$) but resonance states are efficiently mixed, $k_{24} = k_{42} = 2$. Recent quantum mechanical calculation by Zatsarinny *et al* seems to underestimate by factor 2 or more the corresponding cross-sections.

GT1 5 B-spline R-matrix with pseudostates calculations for electron-impact excitation and ionization of aluminum* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* VIKTOR GEDEON, SERGEJ GEDEON, VLADIMIR LAZUR, ELIZABETH NAGY, *Uzhgorod State University* A systematic study of angle-integrated cross sections for electron scattering from neutral aluminum is reported. The calculations, carried out with our B-spline R-matrix with Pseudo-States (BSRMPS) method [1,2], cover elastic scattering, ionization, and excitation of the 14 states $(3s^2np)^2P^o$ $(n = 3-6)$, $(3s^2ns)^2S$ $(n = 4-6)$, $(3s^2nd)^2D$ $(n = 3, 4)$, $(3s3p^2)^{4,2}P$, ^2D, ^2S, and $(3s^24f)^2F^o$ of aluminum. The sensitivity of the predictions is checked by comparing results obtained in different approximations, including a large-scale model with over 500 continuum pseudo-states in the close-coupling expansion. The current results represent an extensive, effectively complete, and highly accurate (believed to be within a few percent) set of electron collision data for neutral aluminum, which is readily suitable for modelling applications.

*This work was supported by the United States National Science Foundation under grants PHY-0903818 and PHY-1212450, and by the XSEDE supercomputer al- location PHY-090031.

[1]O. Zatsarinny, Comp. Phys. Commun. **174**, 273 (2006).
[2]O. Zatsarinny and K. Bartschat, J. Phys. B **47**, 061001 (2014).

GT1 6 Electron impact elastic scattering and vibrational excitation of ethylene* MURTADHA KHAKOO, SABAHA KHAKOO, AHMAD SAKAAMINI, LEIGH HARGREAVES, *Cal State Univ-Fullerton* CARL WINSTEAD, VINCE MCKOY, *Caltech* Experimental and theoretical (Schwinger Multi-Channel model) differential scattering cross sections for low energy electron elastic scattering plus vibrational excitation (4 energy loss features) of ethylene are presented. The incident electron energy range is from 0.5eV to 100eV and scattering angles of 5 to 130 degrees. Comparisons with theory and past available measurements show good agreement in general.

*Funded by a National Science Foundation Collaborative Research Grant to CSUF and Caltech.

GT1 7 Vibrational excitation of methyl chloride by low energy electron impact* MURTADHA KHAKOO, AHMAD SAAKAMINI, LEIGH HARGREAVES, *Cal State Univ- Fullerton* CARL WINSTEAD, VINCE MCKOY, *Caltech* Differential scattering cross sections for low energy vibrational excitation of methyl chloride are presented. The experimental and theoretical (Schwinger Multi-Channel model) results comprise 5 vibrational excitation energy loss features of methyl chloride. The incident electron energy range is from 1 eV to 15 eV and scattering angles from 10 to 130 degrees. Comparisons with other available results will be presented.

*Funded by a National Science Foundation Collaborative Research Grant to CSUF and Caltech.

GT1 8 Electron impact of CO, CO_2, and N_2 using the MAVEN IUVS flight spare* CHARLES P. MALONE, *Jet Propulsion Laboratory* JOSEPH M. AJELLO, *Jet Propulsion Laboratory AND Laboratory for Atmospheric and Space Physics, University of Colorado* ALAN C. HOSKINS, WILLIAM E. MCCLINTOCK, *Laboratory for Atmospheric and Space Physics, University of Colorado* PAUL V. JOHNSON, *Jet Propulsion Laboratory* The Imaging Ultraviolet Spectrograph (IUVS) flight spare, part of the Mars Atmosphere and Volatile and EvolutioN (MAVEN) mission, was used to observe the fluorescence resulting from electron-impact on CO, CO_2, and N_2. The experimental investigation was carried out using a large vacuum chamber, a detector platform that provided vertical and horizontal movement, and the MAVEN IUVS flight spare. An electron gun and Faraday cup, along with suitable Helmholtz coils, were mounted $\sim$ 0.5 m apart and perpendicular to the line-of-sight of the IUVS. The IUVS consists of far-ultraviolet (FUV) and a middle-ultraviolet (MUV) detectors, covering the 110-190 nm and 180-340 nm wavelength ranges, which observed the photon emissions resulting from an optically-thin swarm of gas that was excited by electrons of fixed energies. The imager platform allowed the fluorescence to be observed at multiple vertical positions relative to the on-center measurement, thus enabling direct observation of photons from long-lived metastable states. Absolute emission cross sections, glow profiles, and lifetimes of numerous transitions will be presented.

*Support from NASA's Mars Fundamental Research Program is gratefully acknowledged.

GT1 9 A (e,2e+ion) study of low-energy electron-impact ionization of THF* ESAM ALI, *Missouri Univ of Sci & Tech* XUEGUANG REN, *Max Planck Institute for Nuclear Physics, Heidelberg, Germany* CHUANGANG NING, *Tsinghua University, Beijing, China* ALEXANDER DORN, *Max Planck Institute for Nuclear Physics, Heidelberg, Germany* DON MADISON, *Missouri Univ of Sci & Tech* We have investigated the Fully Differential Cross Sections (FDCS) for electron impact induced ionization of THF (C4H8O) by low-energy (E_o = 26 eV) for three different orbital states of the highest, next highest, and next-next highest occupied molecular orbitals (HOMO, NHOMO, and Next NHOMO). Theoretical results are compared with experiment for in plane scattering with projectile scattering angles of 15°, 25°, 35°, and 50°. Different theoretical models are examined - the molecular 3 body distorted wave (M3DW), and the distorted wave Born approximation (DWBA), with the effects of the post collision interaction (PCI) treated either exactly or with the Ward-Macek approximations.

*This work is supported by the US National Science Foundation under Grant No. PHY-1068237 and XSEDE resources provided by the Texas Advanced Computing Center (Grant No. TG-MCA07S029).

GT1 10 Recombination of H_3^+ Ions with Electrons in Afterglow Plasmas* RAINER JOHNSEN, *University of Pittsburgh* JURAJ GLOSIK, PETR DOHNAL, PETER RUBOVIC, ABEL KALOSI, RADEK PLASIL, *Charles University in Prague* Our past and ongoing flowing and stationary afterglow experiments at temperatures from 60-340 K have resulted in a more complete picture of the plasma recombination of H_3^+ ions: (1) Optical absorption studies indicate that at T = 300 K both para and ortho H_3^+ ions recombine with nearly the same binary coefficient $\alpha_{bin} \sim 0.6 \times 10^{-7}$ cm^3/s. However, at T = 60 K para H_3^+ recombines faster by about a factor of $\sim$10 than does ortho H_3^+. (2) Earlier discrepancies between data obtained in plasmas and those obtained in merged-beam or storage-rings have been traced to ternary recombination due to ambient helium atoms and/or hydrogen molecules. Ternary recombination of H_3^+ due to He or H_2 is more efficient by factors $\sim 10^2$ or 10^5, respectively, than expected from the theoretical model of Bates and Khare for atomic ions. (3) The ternary processes enhance recombination at low third-body densities (10^{17} cm^{-3}) but then level off ("saturate") when their contribution approaches $\sim 1.5 \times 10^{-7}$

cm^3/s. This saturation can lead to the false inference that the overall recombination is binary, resulting in a recombination coefficient that is about 3 times too large. (4) A tentative complex model has been developed that rationalizes the observed effects.

*This work was partly supported by Czech Science Foundation projects GACR 14-14649P and GACR 15-15077S and by Charles University in Prague projects GAUK 692214, GAUK 572214, UNCE 204020/2012 and SVV 260.

GT1 11 Electron impact ionization of CH_4, H_2O and NH_3 with a Sturmian approach* LORENZO UGO ANCARANI, CARLOS MARIO GRANADOS-CASTRO, *Université de Lorraine, France* DARIO M. MITNIK, *IAFE, Buenos Aires, Argentina* GUSTAVO GASANEO, *Universidad Nacional del Sur, Argentina* The study of ionization of molecular systems is more complex and challenging than in the atomic case because the Hamiltonian is generally multicenter and highly non-central. Additionally, in most experiments the molecular spatial orientation is not resolved, so that the random orientation of the molecule must be taken into account through an adequate angular average. In this contribution, we illustrate our implementation of a Sturmian approach, based on Generalized Sturmian Functions [1], for the study of single electron impact ionization of small molecules. Molecular model potentials are proposed to describe the interaction between the ejected electron with the parental ion. A similar approach was used before to study photoionization of molecules [2]. The calculated triple differential cross sections for ionization from valence orbitals of CH_4, NH_3 and H_2O will be reported, and compared with different available theoretical and experimental data.

*We acknowledge the CNRS (PICS project N. 06304) and CONICET (project N. DI 158114) for funding our French-Argentinian collaboration.

[1]G. Gasaneo *et al.*, Adv. Quantum Chem. **57**, 153 (2013).
[2]C. M. Granados-Castro, Adv. Quantum Chem. (2015), accepted for publication.

GT1 12 Primary dissociation channels of SiH4 TOSHIO HAYASHI, KENJI ISHIKAWA, MAKOTO SEKINE, MASARU HORI, *Nagoya University* The primary dissociation channels of SiH4 were investigated using computational chemistry. The results showed the very similar properties to those of CH4. The main dissociation product was SiH2 and the second dissociation product was SiH3. SiH was produced through SiH3 to SiH+H2 reaction, by electronic excitation.

GT1 13 Closed Orbits in Phase Space ANDREW MURPHY, JACE HAESTAD, THOMAS MORGAN, *Department of Physics, Wesleyan University* We report characteristics of closed classical orbits in an electric field in phase space produced in photoabsorption. Rydberg states of atomic and molecular hydrogen and helium are considered. The core potential used for the hydrogen molecule is an effective one electron one center core potential evaluated at the internuclear equilibrium distance. Poincare surfaces of section in phase space are generated by integrating the equations of motion in semiparabolic coordinates $u = (r+z)^{1/2}$ and $v = (r-z)^{1/2}$, and plotting the location in phase space (p_v versus v) whenever $u = 0$, with the electric field in the z direction. Combination orbits produced by Rydberg electron core scattering are studied and the evolution in phase space of these combination orbits due to scattering from one closed orbit into another is investigated. Connections are made to measured laser photoabsorption experiments that excite Rydberg states ($20 < n < 30$) and produce accompanying scaled energy recurrence spectra. The phase space structures responsible for the spectra are identified.

GT1 14 Third-order transport coefficients for electron and positron swarms in gases ILIJA SIMONOVIC, SASA DUJKO, *Institute of physics, University of Belgrade, 11080 Belgrade, Serbia* RONALD WHITE, *James Cook University, Townswille, Australia* ZORAN PETROVIC, *Institute of physics, University of Belgrade, 11080 Belgrade, Serbia* A multi term solution of the Boltzmann equation has been used to calculate third-order transport coefficients of charged particle swarms in neutral gases under the influence of electric and magnetic fields. The hierarchy resulting from a spherical harmonic decomposition of the Boltzmann equation in the hydrodynamic regime is solved numerically by representing the speed dependence of the phase-space distribution function in terms of an expansion in Sonine polynomials about a Maxwellian velocity distribution at an internally determined temperature. A group projector technique is employed to determine the structure and symmetries along individual elements of the skewness tensor when both electric and magnetic fields are present. Results are given for electron and positron swarms for certain model and real gases over a range of electric and magnetic field strengths. The results of the Boltzmann equation analysis are compared with those obtained by a Monte Carlo simulation technique. Various aspects in the behavior of skewness tensor elements are investigated, including the existence of correlation with low-order transport coefficients, sensitivity to post-ionization energy partitioning and errors of two-term approximation for solving Boltzmann's equation.

GT1 15 Experimental and Theoretical Study of Ion Velocity Distribution Functions in Two- Dimensional Velocity Space V. SOUKHOMLINOV, *St. Petersburg State University, Russia* A. MUSTAFAEV, *National Mineral Resources University, St. Petersburg, Russia* H. WANG, A.V. KHRABROV, I.D. KAGANOVICH, *Princeton University* Ion Velocity Distribution Functions (IVDF) in two-dimensional velocity space were measured by one-sided disk probe in He, Ar, N_2, and Hg in the range of dc electric field $\frac{E}{P} \sim 10 \div 20 \frac{V}{cm\,Torr}$, where IVDF is anisotropic and strongly departs from a Maxwellian. Analytical solution of the Boltzmann equation is obtained for IVDF taking into account charge exchange and elastic scattering cross sections. IVDFs were also calculated using Monte Carlo method. Measured and simulated IVDFs agree well with analytical solution and yield known values of mobility and perpendicular and parallel diffusion coefficients.

GT1 16 Collisional quenching reaction rate coefficients of $N_2(A^3\Sigma_u^+)$ by C_2F_6 and C_3F_8 SUSUMU SUZUKI, MASARU KUBOAKI, HARUO ITOH, *Chiba Institute of Technology* The collisional quenching reaction rate coefficient of $N_2(A^3\Sigma_u^+)$ by various air pollutant gases [1,2] were determined from the measurement of the effective lifetime of $N_2(A^3\Sigma_u^+)$in pure N_2 (5-nine) with a small amount of air pollutant gases as an admixture. Derivation of the rate coefficient was performed the waveform analysis of the transient ionization current after turning off the UV light in the Townsend discharge. In this paper, we report that the obtained collisional quenching reaction rate coefficients of $N_2(A^3\Sigma_u^+)$ by C_2F_6 and C_3F_8 are $(2.3 \pm 1.8) \times 10^{-15}$ cm^3/s and $(1.6 \pm 0.8) \times 10^{-14}$ cm^3/s, respectively. Furthermore, we investigate the relationship between the rate coefficient and the mass number of their quenching molecular gases. Firstly, it is confirmed that the rate coefficient take large value with an increase in the mass number of the quenching gases. Secondly, if H atom is included in the gas molecules such as CH_4, C_2F_6 and C_3F_8 the rate coefficient take large value, but if the molecules including F atom such as C_2F_6 and C_3F_8 instead of H atom in this study, more smaller values of the collisional quenching reaction rate coefficient are observed.

[1]S. Suzuki, H. Itoh, H. Sekizawa and N. Ikuta, J. Phys. Soc. Jpn. **62**, 2692 (1992).

[2]S. Suzuki, H. Itoh, Europhysics Conference on Atomic and Molecular Physics of Ionized Gases XXII, P2-03-03 (2014).

GT1 17 PLASMA SCIENCE

GT1 18 Attraction during binary collision of fine particles in Ar plasma MASAHIRO SOEJIMA, TEPPEI ITO, DAISUKE YAMASHITA, NAHO ITAGAKI, HYUNWOONG SEO, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* Forces exerted on fine particles in plasmas play central roles in their transport, agglomeration, as well as Coulomb crystals and liquids. The forces are complicated because of charge fluctuation of fine particles, charge screening in plasma, anisotropy of plasma flow, and so on. Various formulas of such forces have been theoretically predicted but many of them have not been supported by experimental results yet. Here we carried out experiments on binary collision of fine particles using Ar rf-discharge plasmas. PMMA fine particles of 10 μm diameter were injected into the plasma and they were levitated around the plasma sheath boundary. The number of fine particles levitated was so small that we can observe non-collective pair interaction. We observed binary collisions of fine particles with a high speed and high resolution camera. We found that repulsion of two fine particles takes place in short distances, whereas attraction takes place in middle distances. These results indicate that inter-molecular like potential exists between them. The attraction corresponds to non-collective fine-particle attraction due to shadow effects.

GT1 19 Microwave photonic bandgap devices with active plasma elements* BENJAMIN WANG, ROBERTO COLON QUINONES, DAVID BIGGS, THOMAS UNDERWOOD, ANDREA LUCCA FABRIS, MARK CAPPELLI, *Stanford University* STANFORD PLASMA PHYSICS LABORATORY TEAM A 3-D alumina rod based microwave photonic crystal device with integrated gaseous plasma elements is designed and characterized. Modulation of the plasma density of the active plasma elements is shown to allow for high fidelity modulation of the output signal of the photonic crystal device. Finite difference time domain (FDTD) simulations of the device are presented, and the functional effects of the plasma electron density, plasma collision frequency, and plasma dimensions are studied. Experimental characterization of the transmission of the device shows active tunability through adjustments of plasma parameters, including discharge current and plasma size. Additional photonic crystal structures with integrated plasma elements are explored.

*Sponsored by the AFSOR MURI and DOD NDSEG.

GT1 20 NON-EQUILIBRIUM KINETICS OF LOW-TEMPERATURE PLASMAS

GT1 21 A global model study of oxygen discharges – formation and annihilation of the singlet molecular metastables and effects of the electron energy distribution function* MARISA ROBERTO, DAVID ARRUDA TONELI, *Technological Institute of Aeronautics, Sao Jose dos Campos 12228-900, Brazil* RODRIGO SAVIO PESSOA, *Paraiba Valley University, Sao Jose dos Campos 12244-000, Brazil* JON GUDMUNDSSON, *University of Iceland, Reykjavik IS-107, Iceland and KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden* A revised reaction set for oxygen plasma modelling was implemented in a volume average global model that considers only Maxwellian electron energy distribution function. The results showed that the state could be present in the discharge in amounts higher than the state. A further study has been realized through changes in the electron energy distribution function. Differences in the results calculated using Maxwellian and non-Maxwellian distributions demonstrate the importance of using a proper electron energy distribution function in plasma modelling.

*This work was supported by Brazilian Agencies CNPq - (153528/2012-5), CAPES,FAPESP/PRONEX - (2011/50733-0 and 2013/03401-6), the Icelandic Research Fund Grant (130029-053), and the Swedish Government Agency for Innovation Systems (VINNOVA - 2014-04876).

GT1 22 Excitation of $N2(C3\Pi u,v)$ and $N2+(B2\Sigma u+,v)$ vibronic levels by streamer discharge in atmospheric pressure air* TOMAS HODER, *Masaryk University, DPE, Brno, Czech Republic* MILAN SIMEK, *Czech Academy of Sciences, IPP, Prague, Czech Republic* ZDENEK BONAVENTURA, *Masaryk University, DPE, Brno, Czech Republic* Ionizing waves in air often take the form of thin filaments called streamers. Propagating streamer head is a place where the major part of reactive species is produced and that is of considerable interest for various applications, such as pollution control, ozone formation, etc. Knowledge of vibrational distributions of $N2(C3\Pi u,v)$ and $N2+(B2\Sigma u+,v)$ electronic states induced by the streamer head electrons is of particular interest, namely for determination of the self-enhanced electric field in the nitrogen/air streamer discharge. Indeed, vibrational distributions of $N2(C3\Pi u,v)$ and $N2+(B2\Sigma u+,v)$ states are very sensitive to the electric field variations occurring due to the streamer head action and might be used as a complementary spectrometric tool for monitoring streamer head parameters. In this work, a numerical study on streamer induced excitation of $N2(C3\Pi u,v=0\text{-}4)$ and $N2+(B2\Sigma u+,v=0\text{-}4)$ vibronic levels in air is presented and discussed from the point of view of improved determination of the streamer head parameters.

*This research has been supported by the Czech Science Foundation research project 15-04023S.

GT1 23 Correlating Metastable-Atom Density, Reduced Electric Field, and Electron Energy Distribution in the Early Stages of a 1-Torr Argon Discharge JAMES FRANEK, SAM NOGAMI, VLADIMIR DEMIDOV, MARK KOEPKE, *West Virginia University* ED BARNAT, *Sandia National Laboratory* Temporal measurement of electron density, metastable-atom density, and reduced electric field are used to infer the dynamic behavior of the excitation rates describing electron-atom collision-induced excitation in the positive column of a pulsed argon discharge plasma by invoking plausible assumptions regarding the shape of the electron energy distribution function (EEDF), specifically, inelastic electron-metastable collisions produce high-energy electrons and electron-electron collisions will cause the EEDF to become more Maxwellian [1]. Direct observation of these excitation rates have been used to predict the temporal behavior of metastable-atom density in the post-transient stage of a pulsed plasma discharge [2]. Ignoring the Maxwellianizing effect of electron-electron collisions allows for the examination, in this poster, of correlations between the aforementioned quantities in the transient stage of the discharge. We conclude that the observed line-emission ratio and the predicted line-emission ratio are in quantitative agreement with each other in the transient phase of the discharge and qualitatively agree with each other in the initiation phase of the discharge. Ignoring electron-electron collisions allows insight into hard-to-measure or expensive-to-measure plasma conditions and their time dependence in the transient phase of the discharge.

[1]Pitchford *et al.*, J. Appl. Phys. **92**, 6990 .
[2]Franek *et al.*, Plasma Sources Sci. Technol. **24**, 034009 (2015).

GT1 24 Monte Carlo Simulation of the Effect of "Hot" Atoms on Active Species Production in High-Voltage Pulsed Discharges NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* ALEXANDER PONOMAREV, *SSC Keldysh Research Center* ANDREY STARIKOVSKIY, *Princeton University* Atoms and radicals produced in the discharge plasma possess excessive translational energy (a few electron-volts) that is lost after several elastic collisions with neutral particles. It was shown that, prior to the energy degradation of "hot" particles they can be involved in chemical reactions with high energy threshold. This leads to an additional production of chemically active species. The purpose of this work was to simulate numerically this effect and to calculate the amount of active species produced in discharge plasmas taking into account chemical reactions with "hot" atoms and radicals. The simulation was carried out by a Monte Carlo method allowing competitive consideration of elastic and inelastic collisional processes leading to the translational energy relaxation of particles with excessive initial energy. Using a Monte Carlo technique, energy degradation of "hot" H and O atoms was simulated in CH_4:O_2 and CH_4:air mixtures. It was shown that during the relaxation of H and O translational energy the additional generation of CH_3, OH and H2\thinspacetakes place. This affects the total amount and composition of active species produced in high-voltage pulsed discharges.

GT1 25 BASIC PLASMA PHYSICS PHENOMENA IN LOW TERMPERATURE PLASMAS

GT1 26 Mode analysis for a microwave driven plasma discharge: A comparison between analytical and numerical results* DANIEL SZEREMLEY, THOMAS MUSSENBROCK, RALF PETER BRINKMANN, MARC ZIMMERMANNS, ILONA ROLFES, DENIS EREMIN, *None* RUHR- UNIVERSITY BOCHUM, THEORETICAL ELECTRICAL ENGINEERING TEAM, RUHR- UNIVERSITY BOCHUM, INSTITUTE OF MICROWAVE SYSTEMS TEAM The market shows in recent years a growing demand for bottles made of polyethylene terephthalate (PET). Therefore, fast and efficient sterilization processes as well as barrier coatings to decrease gas permeation are required. A specialized microwave plasma source – referred to as the plasmaline – has been developed to allow for depositing thin films of e.g. silicon oxid on the inner surface of such PET bottles. The plasmaline is a coaxial waveguide combined with a gas-inlet which is inserted into the empty bottle and initiates a reactive plasma. To optimize and control the different surface processes, it is essential to fully understand the microwave power coupling to the plasma and the related heating of electrons inside the bottle and thus the electromagnetic wave propagation along the plasmaline. In this contribution, we present a detailed dispersion analysis based on a numerical approach. We study how modes of guided waves are propagating under different conditions, if at all.

*The authors gratefully acknowledge the financial support of the German Research Foundation (DFG) within the framework of the collaborative research centre TRR87.

GT1 27 Measurement of supersonic plasma interacting with stationary plasma by electric probes DONG HAN LEE, IN JE KANG, MIN KEUN BAE, SOON-GOOK CHO, SANG-YOU KIM, HEUNG-GYOON CHOI, SUNG-HOON HONG, *Hanyang Univ* TAE-HYUP LHO, *National Fusion Research Institute* KYU-SUN CHUNG, *Hanyang Univ* Supersonic plasma is generally related to the formation of young star object (YSO), active galactic nuclei (AGN) and new galaxies via plasma bubble expansion during the event of super nova. Capacitive coupled plasma (CCP) is produced by RF power of 13.56 MHz and the plasma is accelerated by negatively biased cascade grid to produce supersonic flow. Electron temperature, plasma density and Mach number are measured by using a single probe and a Mach probe. Electron temperature and plasma density of CCP are 0.8 eV and 1.8×10^9 cm^{-3}, respectively. Mach number of supersonic plasma flow is about 2 and 50 W RF power at 52 mTorr. Ambient plasma is generated by DC filament discharge and its electron temperature and plasma density are 0.5 eV and 3×10^{10} cm^{-3}, respectively. When the supersonic plasma flow interact with ambient plasma, electron temperature is increased higher than ambient plasma up to 4 eV, and plasma density is decreased from 4×10^{10} cm^{-3} to 1×10^{10} cm^{-3}. Density contrast η of supersonic plasma flow of our experiment is about 0.04, while AGN jets in universe are observed to have density contrast η of lower than 10^{-2}.

GT1 28 Streamer discharge inception from a dielectric body with a frequency dependent dielectric permittivity* ANNA DUBINOVA, CASPER RUTJES, UTE EBERT, *Centrum Wiskunde en Informatica (CWI), Amsterdam, Netherlands* Dielectric bodies are polarized by an external electric field; this polarization is characterized by their dielectric permittivity. However, if the electric field changes fast enough, the dipoles inside the dielectrics cannot follow these changes and their dielectric permittivity drops, eventually to 1 for an electric field that changes infinitely fast. Now the characteristic time scale of streamer discharge development at atmospheric pressure is order of nanoseconds. On this time scale many dielectrics respond to a changing electric field with a smaller dielectric permittivity than to a time independent field. Here we study positive streamer inception from a dielectric tip made of ice. The dielectric permittivity of ice drops from 93 to 3 already on the timescale of milliseconds. We demonstrate that this effect is important and that it can make a streamer propagate with only half of the speed as for a constant dielectric permittivity.

*AD acknowledges support by STW project 12119 and CR by FOM-project 12PR3041.

GT1 29 A characterization of atmospheric pressure plasma jets (APPJs) through a spatio-temporal map of the APPJ's optical emission spectra* JAMES KAPALDO, SYLWIA PTASINSKA, *Univ of Notre Dame* APPJs have become increasingly important in the past years in medical, science, and industry. However, there still remains a largely unsolved problem of characterizing APPJs to determine the quantity of species they deliver; the type of atomic, molecular, and radical species they deliver, both charged and neutral; as well as the energy of the species they deliver. In this paper, we will present our work on the characterization of the type of charged species delivered by our APPJ through a spacial and temporal map of the APPJ's optical emission spectra. This spatial-temporal emission spectra enables us to track how the relative abundance of individual emitting species changes as a function of distance from the jets central axis and as a function of time (distance from the APPJ's orifice). Using a helium working gas, we tested our method of characterization by measuring the relative abundances of different helium, nitrogen, and oxygen emitting species under three different conditions: using a shielding gas of oxygen, using a shielding gas of nitrogen, and using no shielding gas at all-just the He jet directly into the atmosphere. The results of this study will be presented.

*The research described herein was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Basic Energy Sciences, Office of Science, United States Department of Energy through Grant No. DE- FC02-04ER15533.

GT1 30 Second harmonic generation as nonlinear bifurcation phenomenon at various positions in plasma-metamaterial composite AKINORI IWAI, *Kyoto University, The University of Shiga Prefecture* YOSHIHIRO NAKAMURA, *Kyoto University* OSAMU SAKAI, *Kyoto University, The University of Shiga Prefecture* Plasma has been a research target as a nonlinear material to generate harmonic waves because of its dynamics. Its nonlinearity has been limited due to the cutoff density beyond which permittivity is negative. Metamaterial is a novel artificial material with extraordinary electromagnetic responses, and an array of double split ring resonators (DSRRs) is a typical one with negative permeability [1]. So far we have successfully confirmed microwave propagation in composites of negative-permeability DSRRs and negative-permittivity plasma whose high electron density enhances its nonlinear phenomena; one of them is second harmonic generation detected at one fixed position along the microwave propagation. In this report, we demonstrate the experimental results about the spatial profiles of the monitored fundamental (2.45 GHz) and the second harmonic (4.9 GHz) wave signals with corresponding measurement of electron density profiles. A significant intensity of the second harmonic wave was detected at a spatially separated position from the input port, which implies that the nonlinearity by the combination of plasma and DSRRs is sustained at overall parts of this composite.

[1]J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. Microw. Theory Tech. **47**, 2075 (1999).

GT1 31 Measurements of Striation Phenomena in Low Energy Atmospheric Pressure Plasma Using the Optical Emission Spectroscopy HIROMASA YAMADA, *University of Tsukuba* HAJIME SAKAKITA, *Innovative Plasma Processing Group, Electronics and Photonics Research Institute, AIST* YUTAKA FUJIWARA, *University of Tsukuba* YUZURU IKEHARA, *Biotechnology Research Institute for Drug Discovery, AIST* JAEHO KIM, SATORU KIYAMA, SUSUMU KATO, MASANORI FUJIWARA, HIROTOMO ITAGAKI, TOMONORI HOTTA, *Innovative Plasma Processing Group, Electronics and Photonics Research Institute, AIST* HAYAO NAKANISHI, *Division of Oncological Pathology, Aichi Cancer Center Research Institute* NOBUYUKI SHIMIZU, *SANNO Hospital (International University of Health and Welfare)* Plasma technology has been used in many fields. It is considered that reactive species produced by plasma play an important role on those plasma applications. There are many unknown phenomena in those application mechanisms. Recently, the striation phenomena was found along the plasma column ejected from a low energy atmospheric pressure plasma equipment using neon gas. In this work, the visible emission of neon plasma flare was measured by using the optical emission spectroscopy, and mainly neon atom and nitrogen molecule neutral lines were observed. Especially, the emission of neon atoms was dominant, and Ne I (683.3 nm) emission intensity of negative current phase was larger than that of positive current phase. Furthermore, the emission distribution of Ne I (683.8 nm) along the striation was measured, and it was found that Ne I also shows intermittent features along the plasma flare.

GT1 32 Radio-frequency sheaths in grazing angle magnetic fields* MILES TURNER, AOIFE SOMERS, HUW LEGGATE, *Dublin City University* Radio-frequency sheaths are a well-known phenomenon in low-temperature plasmas, but they also occur in magnetically confined plasmas designed for fusion applications, particularly when electromagnetic heating techniques are employed. The behaviour of the sheaths in this context is of interest both because of the effect on erosion of plasma facing surfaces by sputtering and possible effects on the stability of the plasma near the wall, with possible consequences for the efficiency of plasma heating. With these problems in mind, in this paper we use a particle-in-cell simulation to investigate the behaviour of a model radio-frequency discharge with a magnetic field at grazing incidence, that is, not quite parallel to, the electrode surface. The plasma parameters are chosen so that, in a normalized sense, they are comparable with those encountered in fusion devices. We discuss the behaviour of the plasma under these conditions, with reference to the adequacy of conventional radio-frequency sheath models under these conditions.

*Work supported by the EUROfusion consortium under grant agreement No 633053.

GT1 33 Ion sound instability driven by the ion flow in a system of the finite length O. KOSHKAROV, A. SMOLYAKOV, *University of Saskatchewan, Saskatoon SK, Canada* I. KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton NJ, USA* V.I. ILGISONIS, *NATIONAL RESEARCH CENTRE "KURCHATOV INSTITUTE", Moscow Russian Federation* Ion sound instabilities driven by the ion flow in a system of a finite length are considered by analytical and numerical methods. The ion sound waves are modified by the presence of stationary ion flow resulting in negative and positive energy modes. The instability develops due to coupling of negative and positive energy modes mediated by reflections from the boundary. It is shown that the wave dispersion due to deviation from quasineutrality is a crucial parameter that determines the stability. In finite length system, the disperson is characterized by the length of the system measured in units of the Debye length. The instability is studied analytically and the results are compared with direct, initial value numerical simulations. It is shown that boundary effects result in the instability under the conditions when the standard kinetic ion sound instability does not occur.

GT1 34 Study on the Striation of an Atmospheric Pressure Plasma Flare Using a High Speed Camera YUTAKA FUJIWARA, *University of Tsukuba* HAJIME SAKAKITA, *National Institute of Advanced Industrial Science and Technology (AIST)* HIROMASA YAMADA, *University of Tsukuba* HIROTOMO ITAGAKI, SATORU KIYAMA, MASANORI FUJIWARA, YUZURU IKEHARA, JAEHO KIM, *National Institute of Advanced Industrial Science and Technology (AIST)* Characteristics of a low energy atmospheric pressure plasma (LEAPP) specially designed for a medical application has been studied by the visualization of plasma emissions using a high speed camera. The formation of striations in the LEAPP was observed between a nozzle exit and a target material. This result indicates that the plasma propagation is not a bullet type. Detail structure of the striation phenomena will be presented in the conference.

GT1 35 A transition of the electron energy distribution function through ratio of driving frequency to the energy relaxation frequency JUNG YEOL LEE, *Pusan National University* JOHN VERBONCOEUR, *Michigan State University* HAE JUNE LEE, *Pusan National University* Over the past twenty years, atmospheric pressure plasma (APP) devices including sub-millimeter dielectric barrier discharges (micro DBDs) have been developed for plasma medicine. They have great advantage of stable and high density plasmas, but there are still many unknown phenomena of which experimental diagnostics are difficult. In this study, a one-dimensional particle-in-cell simulation with Monte Carlo Collisions (MCC) was adopted to investigate the characteristics of electron energy probability function (EEPF) as a self-consistent kinetic model with no assumptions. Spatio-temporal analysis compares well with theoretical estimation of micro DBDs driven with RF frequencies from 13.56 MHz to 500 MHz in APP. The result indicates that the ratio of the driving frequency to the energy relaxation frequency contributes to the drastic transition of EEPF. The kinetic theory with two-term approximation explains that the electron transport follows the non-local kinetics even in the APP device for specific conditions.

GT1 36 PLASMA BOUNDARIES: SHEATHS, BOUNDARY LAYERS, OTHERS

GT1 37 Is the Bohm Criterion satisfied in magnetized plasmas, and how does ion-neutral collisionality matter?* GREG SEVERN, *Dept. of Physics, University of San Diego* JONATHAN GREEN, VICTORIA WINTERS, CHI-SHUNG YIP, NOAH HERSHKOWITZ, OLIVER SCHMITZ, *Dept. of Engineering Physics, University of Wisconsin-Madison* It is taken for granted that the usual Bohm criterion must be satisfied for weakly collisional, magnetized plasmas at the plasma-wall boundary for the case in which the magnetic field is normally incident on the boundary, but there is a paucity of experimental works that confirm it. Beyond this, theorists view the Bohm criterion as approximately true, holding only for collisionless plasmas. The question is whether Bohm's criterion really is satisfied in weakly collisional magnetized plasmas in the simplest case (/B, where is the boundary surface normal vector) and how that criterion (the ions reaching a sonic point at the end of the presheath) is modified as collisionality rises. Experiments are conducted in a linear magnetized helicon plasma source at the University of Wisconsin, Madison, an upgraded version of MARIA (MARIA-Magnetized Anisot Ropic Ion-distribution Apparatus), in order to address these questions. Experimental results are discussed in light of relevant theoretical works.

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GT1 38 Radio-frequency Plasma Sheath Studies NATHANIEL HICKS, *University of Alaska Anchorage* The response of ion-electron plasma as well as two-component plasma to RF fields is studied via PIC simulation. In each case, the light species responds strongly to the RF and the heavy species does not. By varying the external electrode geometry, RF waveform, and driving voltage and frequency, light species of certain charge-to-mass ratios may experience a trapping effect within the RF structure. The space charge of this species creates a potential well for the oppositely-charged, heavy species. Simulation results are presented, as well as plans for experimental investigation of the same effect. Applications to plasma processes in which a plasma boundary is subjected to external RF fields are discussed.

GT1 39 GAS PHASE PLASMA CHEMISTRY

GT1 40 Developing Chemistry and Kinetic Modeling Tools for Low-Temperature Plasma Simulations* THOMAS JENKINS, KRIS BECKWITH, BRADLEY DAVIDSON, SCOTT KRUGER, ALEXEI PANKIN, CHRISTINE ROARK, PETER STOLTZ, *Tech-X Corporation* We discuss the use of proper orthogonal decomposition (POD) methods [1] in VSim, a FDTD plasma simulation code capable of both PIC/MCC and fluid modeling. POD methods efficiently generate smooth representations of noisy self-consistent or test-particle PIC data, and are thus advantageous in computing macroscopic fluid quantities from large PIC datasets (e.g. for particle-based closure computations) and in constructing optimal visual representations of the underlying physics. They may also confer performance advantages for massively parallel simulations, due to the significant reduction in dataset sizes conferred by truncated singular-value decompositions of the PIC data. We also demonstrate how complex LTP chemistry scenarios can be modeled in VSim via an interface with MUNCHKIN, a developing standalone python/C++/SQL code that identifies reaction paths for given input species, solves 1D rate equations for the time-dependent chemical evolution of the system, and generates corresponding VSim input blocks with appropriate cross-sections/reaction rates. MUNCHKIN also computes reaction rates from user-specified distribution functions, and conducts principal path analyses to reduce the number of simulated chemical reactions.

*Supported by U.S. Department of Energy SBIR program, Award DE-SC0009501.

[1]del-Castillo-Negrete *et al.*, PoP **15**, 092308 (2008).

GT1 41 Comparative Shock-Tube Study of Autoignition and Plasma-Assisted Ignition of C_2-Hydrocarbons ILYA KOSAREV, SVETLANA KINDYSHEVA, EUGENY PLASTININ, NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* ANDREY STARIKOVSKIY, *Princeton University* The dynamics of pulsed picosecond and nanosecond discharge development in liquid water, ethanol and hexane Using a shock tube with a discharge cell, ignition delay time was measured in a lean ($\varphi = 0.5$) C_2H_6:O_2:Ar mixture and in lean ($\varphi = 0.5$) and stoichiometric C_2H_4:O_2:Ar mixtures with a high-voltage nanosecond discharge and without it. The measured results were compared with the measurements made previously with the same setup for C_2H_6-, C_2H_5OH- and C_2H_2-containing mixtures. It was shown that the effect of plasma on ignition is almost the same for C_2H_6, C_2H_4 and C_2H_5OH. The reduction in time is smaller for C_2H_2, the fuel that is well ignited even without the discharge. Autoignition delay time was independent of the stoichiometric ratio for C_2H_6 and C_2H_4, whereas this time in stoichiometric C_2H_2- and C_2H_5OH-containing mixtures was noticeably shorter than that in the lean mixtures. Ignition after the discharge was not affected by a change in the stoichiometric ratio for C_2H_2 and C_2H_4, whereas the plasma-assisted ignition delay time for C_2H_6 and C_2H_5OH decreased as the equivalence ratio changed from 1 to 0.5. Ignition delay time was calculated in C_2-hydrocarbon-containing mixtures under study by simulating separately discharge and ignition processes. Good agreement was obtained between new measurements and calculated ignition delay times.

GT1 42 PLASMA-SURFACE INTERACTIONS

GT1 43 Effect of low temperature in nitriding of SiC using a remote M. SHIMABAYASHI, *Hokkaido University, Japan* K. KURIHARA, *Toshiba Corp., Japan* K. SASAKI, *Hokkaido University, Japan* The surface nitriding of SiC using a remote nitrogen plasma is a candidate method for passivating the interface between the gate insulator and the channel region in a SiC-based power transistor. This work was motivated by the decrease in the weight density of the SiC surface by the irradiation of a remote nitrogen plasma. The decrease in the weight density is considered to be mainly due to desorption of C_2N_2 and HCN from the SiC surface during nitriding. In this work, we cooled the SiC sample below -100 °C to minimize the damage induced by the plasma irradiation. The sample which was irradiated by a remote nitrogen plasma for 1 minute showed the following effects of the sample cooling. 1) A deeper nitride layer was formed in the cooled sample, while the dislocation of the crystalline structure was milder. 2) The composition ratio of Si/C was roughly 1/1 in the region at a depth of $>$ 1 nm in the cooled sample. A cooled sample which was irradiated for 3 minutes had a nitride layer without oxygen at a depth of $>$ 1.6 nm. This structure is thought to be stable for the C-face of 4H-SiC. The irradiation of a remote nitrogen plasma to low-temperature SiC could work effectively for forming the passivation layer between the gate insulator and the channel region.

GT1 44 Diagnostic signature of low-energy secondary electron emission at the boundary of a partially-ionized plasma* V.I. DEMIDOV, *WVU* S.F. ADAMS, *AFRL* I.D. KAGANOVICH, *PPPL* M.E. KOEPKE, *WVU* I.P. KURLYANDSKAYA, *ITMO, SPbGU* Effects of secondary electron emission (SEE) from a solid surface in contact with plasma are important for conducting and interpreting plasma experiments and modeling. Those effects are especially strong for contaminated surfaces. Measurements of SEE reported here are conducted in a plasma having a nearly mono-energetic population of electrons that is energetically well resolved and separated from a broader-energy-range electron population. By performing the SEE measurement in an afterglow or afterglow-like plasma, we take advantage of the nearly mono-energetic electron population that arises in ionizing plasma-chemical reactions, such as binary like-particle collisions of metastable atoms. We demonstrate a diagnostic method for measuring the low-energy electron absorption coefficient across the broader energy range and the effects of contamination on the swept-bias probe characteristic trace.

*A part of this research was performed while VID held a National Research Council Research Associateship Award at AFRL.

GT1 45 Current Status of Divertor Plasma Simulator (DiPS-2) for Dust Interactions with Plasma and Surfaces IN JE KANG, SOON-GOOK CHO, MIN KEUN BAE, DONG-HAN LEE, SANG-YOU KIM, SUNG-HOON HONG, HEUNG-GYOON CHOI, *Hanyang University* TAE-HYUP LHO, *National Fusion Research Institute* KYU-SUN CHUNG, *Hanyang University* The divertor plasma simulator (DiPS-2) which is a linear plasma machine with ~ 8 MW/m^2 power density emitted from a DC plasma discharge source with a LaB_6 cathode is under installation for experiments of dust interactions with plasma and surfaces in fusion research fields. Specifications of DiPS-2 have weakly magnetized helium plasmas (density $\sim 10^{13}$ cm^3, electron temperature $\sim$ 1 - 10 eV, particle flux $\sim 10^{23}/(\mathrm{sec}\cdot\mathrm{m}^2)$, which are of the order of plasma parameters in a typical divertor. Currently, a vacuum chamber with the diameter of 560 mm and the length of 800 mm called as "dust interaction with surface chamber (DiSC)" is being setup to an end flange of DiPS-2. The DiSC has a load-lock system for easily changing material targets and plasma diagnostics systems such as laser induced fluorescence (LIF), laser Thomson scattering (LTS), thermocouples and fast scanning probes (FSP) with SP, TP and MP. Using the measured dust and plasma parameters, SOL heat flux width (λ_q) and sheath heat transmission factor (γ_s) will be experimentally deduced for the analysis of the dust effects to plasmas. Initial probe data will be addressed.

GT1 46 Surface charge measurements in barrier discharges on different time scales ROBERT WILD, CHRISTIAN VOLKHAUSEN, JOHANNES BENDUHN, LARS STOLLENWERK, *University of Greifswald* The deposition of surface charge in barrier discharges is a process that influences the ongoing discharge significantly. This contribution presents the measurement of absolute surface charge densities and their dynamics in a laterally extended setup. An electro-optic BSO crystal is used as dielectric. The absolute charge density on its surface is deduced from the change of polarisation of light passing the crystal. Using different temporal resolutions, the behavior of charge is investigated on three different time scales. The highest temporal resolution of the technique is in the order of hundreds of nanoseconds. Therefore it is possible for the first time to observe the charge deposition process during an active discharge. On the time scale of the applied voltage period (several microseconds), the conservation mechanisms of a lateral discharge pattern is investigated. For this, the influence of surface charge and metastable species in the volume is estimated. Further, the behavior of the surface charge spots on a variation of the external voltage and gas pressure is studied. Measurements on a time scale in the magnitude of seconds reveal charge decay and transport phenomena. This work was funded by the Deutsche Forschungsgemeinschaft.

GT1 47 Patterned Surface Functionalization of Dot-Arrayed CNTs for Biochip Sensor Using Scannable Ultrafine Atmospheric Pressure Plasma Jet MITSURU OKADA, *Shizuoka University, Japan* TOMY ABUZAIRI, *Shizuoka University, Japan and Universitas Indonesia, Indonesia* SUDEEP BHATTACHARJEE, *Indian Institute of Technology Kanpur, India* NJI R. POESPAWATI, RENTO W. PURNAMANINGSIH, *Universitas Indonesia, Indonesia* MASAAKI NAGATSU, *Shizuoka University, Japan* The present results show that the feasibility of using a dot-arrayed CNT as a biochip sensor was demonstrated by successfully fabricating CNTs in an array form and performing patterned surface functionalization of amino and carboxyl groups onto CNT. The vertically aligned CNT was fabricated in an array form using a combined thermal-plasma CVD for realizing the development of biochip sensors. Patterned surface functionalization was developed by ultrafine APPJ in two stages: (1) pretreatment by He gas with -500V dc bias and (2) post-treatment without bias by a He/NH3 gas mixture for amino group or by a He/O2 gas mixture for carboxyl group functionalization. The analysis results of chemical derivatization indicate that amino and carboxyl groups successfully functionalized the CNT dot array without interfering with each other. The optimum period of ultrafine APPJ treatments was achieved by balancing the following 3 aspects: (1) effective area of modification, (2) amount of surface functionalization, and (3) damage of the CNT. Finally, the patterned surface functionalization of amino and carboxyl groups was successfully conducted in the arbitrary pattern by using ultrafine APPJ automatically scanned by computer-controlled precision stage.

GT1 48 BCA-kMC Hybrid Simulation for Hydrogen and Helium Implantation in Material under Plasma Irradiation SHUICHI KATO, *Doshisha University, National Institute for Fusion Science* ATSUSHI ITO, *National Institute for Fusion Science, The Graduate University for Advanced Studies* MAMIKO SASAO, *Doshisha University* HIROAKI NAKAMURA, *National Institute for Fusion Science, Nagoya University* MOTOI WADA, *Doshisha University* Ion implantation by plasma irradiation into materials achieves the very high concentration of impurity. The high concentration of impurity causes the deformation and the destruction of the material. This is the peculiar phenomena in the plasma-material interaction (PMI). The injection process of plasma particles are generally simulated by using the binary collision approximation (BCA) and the molecular dynamics (MD), while the diffusion of implanted atoms have been traditionally solved by the diffusion equation, in which the implanted atoms is replaced by the continuous concentration field. However, the diffusion equation has insufficient accuracy in the case of low concentration, and in the case of local high concentration such as the hydrogen blistering and the helium bubble. The above problem is overcome by kinetic Monte Carlo (kMC) which represents the diffusion of the implanted atoms as jumps on interstitial sites in a material. In this paper, we propose the new approach "BCA-kMC hybrid simulation" for the hydrogen and helium implantation under the plasma irradiation.

GT1 49 Cross correlation analysis of plasma perturbation in amplitude modulated reactive dusty plasmas TEPPEI ITO, MASAHIRO SOEJIMA, DAISUKE YAMASHITA, HYUNWOONG SEO, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, TATSUYA KOBAYASHI, SHIGERU INAGAKI, *Kyushu University* Interactions between plasmas and nanointerface are one of the most important issues in plasma processing. We have studied effects of plasma perturbation on growth of nanoparticles in amplitude modulated reactive dusty plasmas and have clarified that amplitude modulation (AM) leads to suppression of growth of nanoparticles [1]. Here we report results of cross correlation analysis of time evolution of laser light scattering intensity from nanoparticles in reactive plasmas. Experiments were carried out using a capacitively-coupled rf discharge reactor with a two-dimensional laser light scattering (LLS) system. We employed Ar+DM-DMOS discharge plasmas to generate nanoparticles. The peaks at higher harmonics and subharmonics in spectra of laser light scattering intensity were detected, suggesting nonlinear coupling between plasma and nanoparticle amount. We found high cross correlation t between waves at AM frequency and its higher harmonics. Namely, perturbation at f_{AM} closely correlates with those at higher harmonics.

GT1 50 Study of the secondary electron emission in the limit of low electron energies using Q-machine in transverse magnetic field ALEXANDER MUSTAFAEV, *National Mineral Resources University (Mining University)* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory* VLADIMIR DEMIDOV, *West Virginia University* ARTIOM GRABOVSKIY, *National Mineral Resources University (Mining University)* The secondary electron emission (SEE) from surfaces plays an important role in plasma, accelerator and high power microwave applications [2,3]. A recent study proposed that the SEE yield, which is ratio of secondary to primary electron fluxes, approaches unity in the limit of zero energy of incident electron [3]. The high SEE has profound implications especially for plasma applications, including, for example, plasma thrusters for spacecraft propulsion and electric probes. High SEE at low electron energies may be caused by variety of surface effects. In specially cleaned metal surfaces numerous previous experimental studies of the secondary electron emission did not observed high SEE [1]. This talk presents a technique for measurements of SEE yield in a low-pressure plasmas in the presence of transverse magnetic field. It is shown that for poly-crystal surfaces, the SEE yield can be indeed very high (~ 0.8) but still not approaching unity. This result is explained by additional reflection of primary electrons from a potential barrier near the poly-crystal surface. The contribution of electron reflection from the potential barrier and the surface has been identified and studied.

[1]A. Andronov, I. Kaganovich *et al.*, Bull. of the APS **58**, 306 (2013).
[2]A. Mustafaev, M. Kaganovich *et al.*, Bull. of the APS **58**, 62 (2013).
[3]R. Cimino *et al.*, Phys. Rev. Lett. **93**, 014801 (2004).

GT1 51 Ablation of CsI by XUV Capillary Discharge Laser PETER PIRA, ZDENEK ZELINGER, *J. Heyrovsky Institute of Physical Chemistry of the Academy of Sciences of the Czech Republic, v. v. i., Dolejskova 2155/3, 182 23 Praha 8, Czech Repu* TOMAS BURIAN, LUDEK VYSIN, *Institute of Physics of the Academy of Sciences of the Czech Republic,v.v.i., Na Slovance 2, 182 21 Praha 8, Czech Republic* JAN WILD, *Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, 180 00 Praha 8, Czech Republic* LIBOR JUHA, *Institute of Physics of the Academy of Sciences of the Czech Republic,v.v.i., Na Slovance 2, 182 21 Praha 8, Czech Republic* JAN LANCOK, *Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, 180 00 Praha 8, Czech Republic* VACLAV NEVRLY, *Faculty of Safety Engineering, VSB - Technical University of Ostrava, Lumirova 630/13, 700 30 Ostrava, Czech Republic* XUV capillary discharge laser (CDL) is suitable source for ablation of ionic crystals as material which is difficult to ablate by conventional laser. Single crystal of CsI was irradiated by 2.5 ns pulses of a 46.9 nm radiation at 2 Hz. The CDL beam was focused by Sc/Si multilayer spherical mirror. Attenuation length of CsI for this wavelength is 38 nm. Ablation rate was calculated after irradiation of 10, 20, 30, 50 and 100 pulses. Depth of the craters was measured by optical profiler (white light interferometry). Ablation threshold was determined from craters after irradiation with the changing fluence and compared with modeling by XUV-ABLATOR.

GT1 52 Active interrogation of plasma-liquid boundary using 2D plasma-in-liquid apparatus* JANIS LAI, JOHN FOSTER, *University of Michigan* Plasma medicine and plasma-based water purification technologies rely on the production and transport of plasma-derived (direct or indirect) reactive species into the bulk medium. This interaction takes place at the interface between the gas phase plasma and the liquid medium. The nature of radical production and subsequent radical transport from this region or boundary layer is not well understood due to the difficulty of implementing diagnostics to interrogate this region. We present a 2-D plasma-in-liquid water apparatus that makes the interface region assessable to optical diagnostics. Using colorimetric chemical probes, acidification and oxidation fronts are tracked using high-speed imaging and spectroscopy. Additionally, observed, plasma-induced fluid dynamical effects are also discussed. Forces at the interface can play a key role in the transport of radicals into the bulk solution. The role of plasma-driven interfacial forces as well as that of the applied, local electric field on chemical front propagation velocity and induced circulation are also discussed.

*Supported by grants NSF CBET 1336375 and DOE DE-SC0001939.

GT1 53 Modifications in Structural, Electrical, Electronic and Mechanical Properties of Titanium Thin Films under different Gas Plasmas* OMVEER SINGH, RAJ P. DAHIYA, HITENDRA K. MALIK, *Indian Inst of Tech-New Delhi* In the recent past, Titanium thin films can be grown over different substrates such as silicon, glass and quartz by using versatile deposition techniques DC, RF sputtering, electronic beam and thermal evaporation etc. The grown films are then exposed in different gas environments for individual application. It has been found that Titanium nitride exhibits good chemical stability, mechanical and electrical properties. To investigate these properties in titanium nitride thin films, we have developed a new approach hot cathode arc discharge plasma system. By using this technique, we can measure plasma and nitriding parameters independently. In the present work, we have investigated gases mixture (Nitrogen, Argon and Hydrogen) effect on the structural, mechanical, electrical and electronic properties in plasma system. We have used 100% N2, 50% N2 + 50% Ar and 50% N2 + 50% H2 gases ratio for plasma nitriding. Structural and electronic structure properties are measured from X-ray diffractions (XRD) and X-ray photoelectron spectroscopy (XPS) respectively. The surface morphology of these films were measured using Atomic Force Microscopy (AFM) and the nano-indentation mode is used to find out the hardness of the samples.

*Government of India.

GT1 54 The Effect of Anode Material and Secondary Gas Injection on Self-organized Patterns in Atmospheric Pressure Glows* YAO KOVACH, JOHN FOSTER, *University of Michigan — Ann Arbor* Plasma self-organization on anode surfaces in DC glow discharges remains poorly understood. This effort aims to elucidate the nature of self-organization through the study of resulting patterns on both liquid and metal electrode surfaces. Self-organization pattern formation and behavior were studied as a function of inter-electrode spacing, electrode material type, gas composition and gas flow rate using emission spectroscopy and fast camera imaging. The response of the patterns to variation in these parameters is reported. These results are used as a basis for speculating upon the underlying physical processes that give rise to the self-organization.

*NSF CBET 1336375.

GT1 55 Plasma surface kinetics studies of etch process in inductively coupled fluorocarbon and hydrogen-containing fluorocarbon plasmas WON-SEOK CHANG, *Plasma Technology Research Center, National Fusion Research Institute* DONG-HUN YU, *Kyung-Won Tech.Inc* DEOG-GYUN CHO, YEONG-GEUN YOOK, POO-REUM CHUN, SE-AH LEE, *Chonbuk National University* DEUK-CHUL KWON, *Plasma Technology Research Center, National Fusion Research Institute* YEON-HO IM, *Chonbuk National University* Ultra-high deep contact-hole etching is one of the critical issues in fabrication processes of the nanoscale devices. The fluorocarbon (FC) plasmas have been used to obtain the ideal etch profiles. To achieve ultra-high deep contact hole, we present a plasma-surface kinetic studies based on the experimental plasma diagnostic data for silicon dioxide and nitride etch process under inductively coupled FC and HFC plasmas. For this work, the cut-off probe and QMS were used for measuring the electron densities and the ion and neutral radical species. Furthermore, the systematic surface analysis was performed to investigate the thickness and chemical bonding of polymer passivation layer during the etch process. The proposed semi-global surface kinetic model can consider deposition of polymer passivation layer and silicon oxide & nitride etching self-consistently. In this model, thickness of the passivated polymer layer on substrate is calculated from steady-state polymer consumption balance which is composed of sputtered consumption and polymer deposition during oxide etching. Finally, this work will provide better insights to understand basic phenomena of the plasma etching process, leading to the predictable and reliable 3D topography simulation (K-SPEED).

GT1 56 PLASMA DIAGNOSTIC TECHNIQUES

GT1 57 Spectroscopic Examination of Molecular Spectra in Mixture Gaseous Microwave Discharge (N2-O2 and N2-H2) HAO TAN, ATSUSHI NEZU, HIROSHI AKATSUKA, *Tokyo Institute of Technology* We develop some theoretical calculations of spectra of molecular electronic transitions. By using spectroscopic measurement, spectra range at 200-800-nm can be obtained and are compared with the calculation results to exam the molecular properties. We use N_2-H_2 microwave discharge to exam NH and N_2-O_2 microwave discharge to exam NO.

GT1 58 Real-time monitoring of GaN films in processing plasma YOSHITSUGU BANNNO, YOSHITAKA NAKANO, DAISUKE OGAWA, KEIJI NAKAMURA, *Chubu University* The use of plasma is expected when fabricating devices on a gallium nitride (GaN) substrate. However, the plasma can make some significant damages that are caused by irradiating particles etc., in particular, high-energy ions generated in the plasma. In order to understand the mechanism to create these damages, we so far utilized photoluminescence (PL) emissions from the GaN film to make real-time monitoring of any changes relating to optical properties of the film that was exposed in the plasma. In this presentation, we will show our preliminary measurements with PL from the GaN exposed in argon or argon-chlorine plasma. Argon plasma is expected to give physical damages, while chlorine-containing plasma is expected to give both physical and chemical damages. Our measurements showed that the exposure in argon plasma degraded PL emission property from the GaN film, while the exposure of chlorine-containing plasma did not. This is likely because the speed of chemical reactions (etching) was simply faster than the speed of creation of physical damages according to our thickness measurement. Our presentation will give the following results from the real-time monitoring measurements.

GT1 59 Evaluation of Plasma Temperature from the OH Violet Molecular Emission System HOSSEIN NASSAR, OULOUM AOUDE, *Lebanese University-Faculty of Public Health section4* The violet OH system ($A^2\Sigma^+$ - $X^2\Pi_i$) molecular emission spectrum is frequently observed in plasma sources containing water it is a good tool for diagnosing plasmas containing this molecule. We have simulated the spectrum of (0,0) band of this system from 3064 Å for different rotational temperature. The method proposed permit to evaluate, by comparing point to point a real spectrum with the simulated one, temperature and apparatus function, approximated by the gauss function (the half-width at 1/e height). Moreover, it is shown, by noised spectra simulation, the influence of noise to signal ratio at the calculated temperature values. If the noise to signal ratio is about 10% we found an error of 6% at temperature 3000 K and 10% at 6000 K. This method has been used to determine the combustion temperature from a real spectrum recording in Polymethyl methacrylate rocket plume taken 0 mm from the nozzle of fuel grain. The rotational temperature of about 3000 ± 350 K, has been found and noise to signal ratio is about 20%.

GT1 60 Investigation on measurement of effective sheath width using a cutoff probe JUNG-HYUNG KIM, DAE-WOONG KIM, *Korea Research Institute of Standards and Science* SHIN-JAE YOU, *Physics department, Chungnam National University, Daejeon, Republic of Korea* The plasma density is the key parameter showing electric plasma property as well as processing rate. Therefore, various diagnostic methods have been developed and researched for measuring the absolute plasma density. One of them, cutoff probe, has been developed for more accurate measurement of the plasma density. The cutoff probe is the promising diagnostics method having diagnostic advantages: high accuracy in measured plasma density, simple assumption in measurement process, and readily use and interpretation of results for diagnostics. The sheath is also an important parameter in plasma researches and applications. In this presentation, we introduce measurement method of the effective sheath width using equivalent circuit model of S21 phase spectrum of the cutoff probe. The reliability of this method was verified by investigation of the FDTD simulation and comparative experiment with calculated Child-Langmuir law sheath width from Langmuir probe data. The results show that measured sheath width has an acceptable error when it was compared with input sheath width in the FDTD simulation. Furthermore, the measured sheath width was found to be in good agreement with the floated sheath width calculated from the Child-Langmuir sheath law.

GT1 61 Matched dipole probe for precise electron density measurements in magnetized and non-magnetized plasmas* DMYTRO RAFALSKYI, ANE AANESLAND, *LPP - École Polytechnique* We present a plasma diagnostics method based on impedance measurements of a short matched dipole placed in the plasma. This allows measuring the local electron density in the range from 10^{12}-10^{15} m^{-3} with a magnetic field of at least 0-50 mT. The magnetic field strength is not directly influencing the data analysis and requires only that the dipole probe is oriented perpendicularly to the magnetic field. As a result, the magnetic field can be non-homogeneous or even non-defined within the probe length without any effect on the final tolerance of the measurements. The method can be applied to plasmas of relatively small dimensions (< 10 cm) and doesn't require any special boundary conditions. The high sensitivity of the impedance measurements is achieved by using a miniature matching system installed close to the probe tip, which also allows to suppress sheath resonance effects. We experimentally show here that the tolerance of the electron density measurements reaches values lower than 1%, both with and without the magnetic field. The method is successfully validated by both analytical modeling and experimental comparison with Langmuir probes. The validation experiments are conducted in a low pressure (1 mTorr) Ar discharge sustained in a 10 cm size plasma chamber with and without a transversal magnetic field of about 20 mT.

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GT1 62 Optical emission spectroscopy of argon and hydrogen-containing plasmas* SARAH SIEPA, *Institute for Experimental Physics II, Ruhr-University Bochum, Germany* STEPHAN DANKO, *Robert Bosch GmbH, Germany* TSANKO V. TSANKOV, *Institute for Experimental Physics V, Ruhr-University Bochum, Germany* THOMAS MUSSENBROCK, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum, Germany* UWE CZARNETZKI, *Institute for Experimental Physics V, Ruhr-University Bochum, Germany* Optical emission spectroscopy (OES) on neutral argon is applied to investigate argon, hydrogen and hydrogen-silane plasmas. The spectra are analyzed using an extensive collisional-radiative model (CRM), from which the electron density and the electron temperature (or mean energy) can be calculated. The CRM also yields insight into the importance of different excited species and kinetic processes. The OES measurements are performed on pure argon plasmas at intermediate pressure. Besides, hydrogen and hydrogen-silane plasmas are investigated using argon as a trace gas. Especially for the gas mixture discharges, CRMs for low and high pressure differ substantially. The commonly used line-ratio technique is found to lose its sensitivity for gas mixture discharges at higher pressure. A solution using absolutely calibrated line intensities is proposed. The effect of radiation trapping and the shape of the electron energy distribution function on the results are discussed in detail, as they have been found to significantly influence the results [1].

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[1]S. Siepa *et al.*, J. Phys. D: Appl. Phys. **47**, 445201 (2014).

GT1 63 Ion energy distributions in dual frequency RF plasmas PETER HATTON, JOHN REES, SAM BORT, DAVE SEYMOUR, *Hiden Analytical Ltd* For many surface-processing applications involving plasmas operated at RF frequencies it has been found helpful to combine two sources of power operating at different frequencies. By choosing suitable input powers at the two frequencies and varying the phase relationship set between the two inputs, the energy distributions (IEDs) for the ions arriving at the target surface can be optimised. There have been, however, only a limited number of published reports of measured or modelled distributions. In the present work IEDs for both positive and negative ions formed in plasmas in argon and nitrous oxide have been measured for mass-identified ions in two different reactors, one of which is a parallel-plate, capacitatively-coupled, system and the other is an inductively-coupled system. Typical data for 13.56 and 27.1 MHz inputs are presented for a range of phase relationships. The IEDs show clearly significant differences between the data for different species of ions which result in part from the ion-molecule collisions occurring, particularly in the plasma/surface sheath regions.

GT1 64 Quantification of the VUV radiation in low pressure hydrogen and nitrogen plasmas URSEL FANTZ, *Max-Planck-Institut fuer Plasmaphysik* STEFAN BRIEFI, *Universitaet Augsburg* DAVID RAUNER, DIRK WUENDERLICH, *Max-Planck-Institut fuer Plasmaphysik* Low pressure plasmas with hydrogen and/or nitrogen emit intense radiation in a broad wavelength region in the VUV. In order to quantify this radiation measurements in the wavelength region from 120 nm to 280 nm have been carried out using RF discharges. In case of molecular hydrogen dominant transitions are the Werner band (C–X), the Lyman band (B–X), and the continuum (a–b) as well as the Lyman lines from the hydrogen atom. Depending on the pressure, for hydrogen up to 20% of the RF power of 600 W, is found in the VUV, whereas only about 2% are emitted in the VIS represented by the Balmer series emission (H_α - H_δ) and the Fulcher emission (d–a). For nitrogen, the Lyman-Birge-Hopfield system (a-X) is most prominent in the wavelength region between 125 nm and 230 nm as well as some nitrogen resonance lines whereas in the visible range the first and second positive systems dominate. In hydrogen-nitrogen mixtures NH radiation appears due to the plasma chemistry. The measured radiant power will be compared with results from collisional radiative models for H_2 and N_2 which make use of electron density and temperature from spectroscopic measurements. Extrapolations to a wider parameter range are provided.

GT1 65 Sheath capacitance measurement in inductively coupled plasmas JIN-YONG KIM, CHIN-WOOK CHUNG, *Hanyang University* Sheath capacitance was measured with a floating probe in inductively coupled plasmas. In order to measure the sheath capacitance, two frequencies of small AC voltage signals were applied to the floating probe. The amplitudes of AC currents and an equivalent sheath circuit model were used for the calculation of the sheath capacitance. The experiments were performed at various plasma states and our experimental results were in good agreements with previous studies.

GT1 66 Improved tunable external filter for Langmuir probe measurement at low density plasmas YOON-MIN CHANG, HYO-CHANG LEE, SANG-BUM JEON, DONG-HWAN KIM, JU-HO KIM, CHIN-WOOK CHUNG, *Hanyang University* DEPARTMENT OF ELECTRICAL ENGINEERING TEAM, DEPARTMENT OF NANOSCALE SEMICONDUCTOR ENGINEERING TEAM Measurement of the electron energy probability function (EEPF) at low density plasma, especially in molecular gas discharge, is difficult due to large RF fluctuation. To overcome the problem, an improved tunable external filter was developed. In contrast to an internal filter, the external filter can tune the resonance frequency of the choke filter. However, conventional external filter has low impedance due to a large stray capacitance between a probe tip and the external filter. To reduce the effect of the stray capacitance, an appropriate inductor was connected to the probe tip, and the external filter was designed to tune the first and the second harmonic frequencies independently. Using our filter, the EEPFs were measured at low density plasma with various gases, and the results show the improved performance of the filter as compared to the previous studies.

GT1 67 Two-dimensional time-resolved measurement of plasma parameters on a wafer-level using floating harmonic method IL-SEO PARK, KWAN-YONG KIM, DONG-HWAN KIM, YUSIN KIM, CHIN-WOOK CHUNG, *Hanyang University* DEPARTMENT OF ELECTRICAL ENGINEERING TEAM, DEPARTMENT OF NANOSCALE SEMICONDUCTOR ENGINEERING TEAM Two-dimensional time-resolved plasma diagnostic system is developed to observe transient plasma behaviors. The system is composed of wafer-type probe array, 16-channel/simultaneous data acquisition system, and driving circuit for floating harmonic method (FHM). The FHM can measure the electron density and electron temperature with high time resolution up to 200 microsec. By using the diagnostic system, transient plasma behaviors, such as effects of gas inlet and antenna power absorption, were observed. When the gas is distributed non-uniformly, the plasma density is relatively high near the gas inlet. In addition, antenna-shape plasma profiles are observed when the plasma is turned on and off.

GT1 68 Sensitivity Enhancement of RF Plasma Etch Endpoint Detection With K-means Cluster Analysis* HONYOUNG LEE,† HAEGYU JANG,‡ HAK-SEUNG LEE,§ HEEYEOP CHAE,‖ *Sungkyunkwan Univ* Plasma etching process is the core process in semiconductor fabrication, and the etching endpoint detection is one of the essential FDC (Fault Detection and Classification) for yield management and mass production. In general, Optical emission spectrocopy (OES) has been used to detect endpoint because OES can be a non-invasive and real-time plasma monitoring tool. In OES, the trend of a few sensitive wavelengths is traced. However, in case of small-open area etch endpoint detection (ex. contact etch), it is at the boundary of the detection limit because of weak signal intensities of reaction reactants and products. Furthemore, the various materials covering the wafer such as photoresist, dielectric materials, and metals make the analysis of OES signals complicated. In this study, full spectra of optical emission signals were collected and the data were analyzed by a data-mining approach, modified K-means cluster analysis. The K-means cluster analysis is modified suitably to analyze a thousand of wavelength variables from OES. This technique can improve the sensitivity of EPD for small area oxide layer etching processes: about 1.0% oxide area. This technique is expected to be applied to various plasma monitoring applications including fault detections as well as EPD.

*Plasma Etch, EPD, K-means Cluster Analysis.
†School of Semiconductor and Display Engineering.
‡SKKU Advanced Institute of Nanotechnology (SAINT).
§School of Chemical Engineering.
‖Corresponding Auther, Professor , School of Chemical Engineering.

GT1 69 Spatial Resolution of Combined Wavelength Modulation Spectroscopy with Integrated Cavity Output Spectroscopy for Atomic Oxygen Detection MAKOTO MATSUI, DAISUKE NAKAJIMA, *Shizuoka Univ* For developments of thermal protection system, atomic oxygen plays important role. However, its measurement method has not been established because the pressure in front of TPS test materials is as high as a few kPa. Our group proposed combined wavelength modulation and integrated output spectroscopies based on the forbidden transition at OI 636 nm to measure the ground-state number densities. In this study, WM-ICOS system is developed and applied to a microwave oxygen plasma to evaluate measurable region. As a result, the estimated number density by ICOS could be measured as low as 10^{21} m^{21}. For the condition, WM-ICOS was applied. The signal to noise ratio of the 2f signal was 40.4. Then, the sensitivity was improved about 26. This result corresponding to the measurement limit of the partial atomic oxygen pressure of 250 Pa. The sensitivity of WM-ICOS was found to enough to diagnose the shock layer in high enthalpy flows. However, the spatial resolution was as large as 8 mm. The size of the beam pattern depends on the cavity length, robust ness of the cavity and accuracy of the cavity alignment. In this presentation, the relationship among these parameters will be discussed.

GT1 70 Quantification Approach of Gas Temperate Distribution in Atmospheric Positive DC Glow Discharge Measured by Spectroscopic Imaging RYO SASAMOTO, HIDEAKI ORII, TAKAO MATSUMOTO, YASUJI IZAWA, KIYOTO NISHIJIMA, *Department of Electrical Engineering, Fukuoka University* In our previous work, a two-dimensional (2D) gas temperature distribution in a positive DC steady-state glow corona was qualitatively measured by spectroscopic imaging. Spectral images of its glow corona were taken using ICCD camera with ultra-narrow band-pass filters, and they were corresponded to the head and tail of a second positive system bands of nitrogen (2PS N_2 (0-2)). The qualitative gas temperature was obtained from the emission intensity ratio (I_{2Ptail}/I_{2Phead}) between the head and tail of 2PS N_2 (0-2). This emission intensity ratio also equals the rotational temperature (T_R), and T_R almost equals the gas temperature (T_G) in atmospheric pressure. In this work, the qualitative 2D gas temperature distribution was derived from 2D I_{2Ptail}/I_{2Phead} plots, and the calibration date of I_{2Ptail}/I_{2Phead} for T_R was accumulated by investigating the relationship between the spatially average absolute gas temperature (T_{av}) obtained by single-point spectroscopic measurement and the average value of I_{2Ptail}/I_{2Phead} plots. On the basis of the calibration date, a spectroscopically-imaged qualitative 2D I_{2Ptail}/I_{2Phead} distribution in a positive DC glow corona was converted to a quantitative 2D image of gas rotational temperature.

GT1 71 Three electrode atmospheric pressure plasma jet in helium flow* DEJAN MALETIC, NEVENA PUAC, GORDANA MALOVIC, ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia* Plasma jets are widely used in various types of applications and lately more and more in the field of plasma medicine. However, it is not only their applicability that distinguishes them from other atmospheric plasma sources, but also the behavior of the plasma. It was shown that plasma plume is not continuous, but discrete set of plasma packages. Here we present iCCD images and current voltage characteristics of a three electrode plasma jet. Our plasma jet has a simple design with body made of glass tube and two transparent electrodes wrapped around it. The additional third metal tip electrode was positioned at 10 and 25 mm in front of the jet nozzle and connected to the same potential as the powered electrode. Power transmitted to the plasma was from 0.5 W to 4.0 W and the helium flow rate was kept constant at 4 slm. For the 10 mm configuration plasma is ignited on the metal tip in the whole period of the excitation signal and in the positive half cycle plasma "bullet" is propagating beyond the metal tip. In contrast to that, for the 25 mm configuration at the tip electrode plasma can be seen only in the minimum and maximum of the excitation signal, and there is no plasma "bullet" formation.

*This research has been supported by the Ministry of Education, Science and Technological Development, Republic of Serbia, under projects ON171037 and III41011.

GT1 72 Measurement of the negative hydrogen ions temperature by using an omegatron mass analyzer in the sheet plasma TOSHIKIO TAKIMOTO, TAKAAKI IIJIMA, YUTA TANAKA, TAKUYA HASE, AKIRA TONEGAWA, *Tokai University* KOHNOSUKE SATO, *Chubu Electric Power Co.Inc.* KAZUTAKA KAWAMURA, *Tokai University* The production mechanisms of negative ions in hydrogen plasma are not easily understood because of the complex phenomena of atomic and molecular reactions. A mainstream measurement of H^- is a laser photodetachment technique. We had measured negative ions using a laser photodetachment technique. Consequently, under a secondary hydrogen gas supply entering into the plasma, the H^- is distributed in the periphery of the sheet plasma. In addition, it has been reported that the negative hydrogen ions transport velocity evaluated by the relaxation time of optically released electron current. Nevertheless, this technique a laser photodetachment cannot be used as a mass analyzer. In this paper, we have measured the temperature of the negative hydrogen ions T_{H-} by using an omegatron mass analyzer in the sheet plasma. The T_{H-} is determined by measuring the collection ion currents I_{H-} as a function of the ion repeller voltage V_{G2} by using an omegatron mass analyzer. From the fitting an exponential region of the measured I-V characteristics curve, T_{H-} is around 1.40 eV at the gas pressure of 0.23 Pa in the periphery region of the sheet plasma.

GT1 73 Laser Thomson scattering in a pulsed atmospheric arc discharge BRADLEY SOMMERS, STEVEN ADAMS, *Air Force Research Laboratory, Wright-Patterson AFB* Laser scattering measurements, including Rayleigh, Raman, and Thomson scattering have been performed on an atmospheric pulsed arc discharge. Such laser scattering techniques offer a non-invasive diagnostic to measure gas temperature, electron temperature, and electron density in atmospheric plasma sources, particularly those with feature sizes approaching 1 mm. The pulsed discharge is ignited in a pin to pin electrode geometry using a 6 kV pulse with 10 ns duration. The electrodes are housed in a glass vacuum chamber filled with argon gas. The laser signal is produced by a Nd:Yag laser supply, repetitively pulsed at 10 Hz and frequency quadrupled to operate at 266 nm. The scattered laser signal is imaged onto a triple grating spectrometer, which is used to suppress the Rayleigh scatter signal in order to measure the low amplitude Thomson and Raman signals. Preliminary results include measurements of electron temperature and electron density in the plasma column taken during the evolution of the discharge. The laser system is also used to measure the Rayleigh scattering signal, which provides space and time resolved measurements of gas temperature in the arc discharge.

GT1 74 Diagnostics of capacitively-coupled hydrocarbon plasmas for deposition of diamond-like carbon films using quadrupole mass spectrometry and Langmuir probe* AKINORI ODA, *Faculty of Engineering, Chiba Institute of Technology* SHUN FUKAI, *Graduate School of Engineering, Chiba Institute of Technology* HIROYUKI KOUSAKA, *Graduate School of Engineering, Nagoya University* TAKAYUKI OHTA, *Faculty of Engineering, Meijo University* Diamond-like carbon (DLC) films are the hydrogenated amorphous carbon films, which contains a mixture of sp^2- and sp^3-bonded carbon. The DLC films have been widely used for various applications, such as automotive, semiconductors, medical devices, since have excellent material properties in lower friction, higher chemical stability, higher hardness, higher wear resistance. Until now, numerous investigations on the DLC films using plasma assisted chemical vapor deposition have been done. For precise control of coating technique of DLC films, it is enormously important to clarify the fundamental properties in hydrocarbon plasmas, as a source of hydrocarbon ions and radicals. In this paper, the fundamental properties in a low pressure radio-frequency hydrocarbon (Ar/CH_4(1%) gas mixture) plasmas have been diagnosed using a quadrupole mass spectrometer (HIDEN ANARYTICAL Ltd., EQP-300) and Langmuir probe system (HIDEN ANARYTICAL Ltd., ESPion).

*This work was partly supported by KAKENHI (No.26420247), and a "Grant for Advanced Industrial Technology Development (No.11B06004d)" in 2011 from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

GT1 75 Laser induced fluorescence measurements of ion velocity in a DC magnetron microdischarge with self-organized drift wave modes propagating in the direction opposite the E x B electron drift velocity* CHRIS YOUNG, NICOLAS GASCON, ANDREA LUCCA FABRIS, MARK CAPPELLI, *Stanford University* TSUYOHITO ITO, *Osaka University* STANFORD PLASMA PHYSICS LABORATORY COLLABORATION, OSAKA

UNIVERSITY CENTER FOR ATOMIC AND MOLECULAR TECHNOLOGIES COLLABORATION Evidence is presented of rotating azimuthal wave structures in a planar DC magnetron microdischarge operating in argon and xenon. Plasma emission captured using a high frame rate camera reveals waves of varying azimuthal modes propagating in the negative E x B direction. The dominant stable mode structure depends on discharge voltage. The negative drift direction is attributed to a local field reversal arising from strong density gradients that drive excess ions towards the anode. The transition between modes is shown to be consistent with models of gradient drift-wave dispersion in the presence of such a field reversal when the fluid representation includes ambipolar diffusion along the direction parallel to the magnetic field. Time-average and time-synchronized laser induced fluorescence measurements are carried out to elucidate the anode-bound ion dynamics driven by the field reversal.

*This research is supported by the Air Force Office of Scientific Research.

GT1 76 Emission Spectroscopy measurement of hybrid ECR-Helicon plasma source parameters AHMED HALA, *KACST* Optical emission spectroscopy measurement of plasma temperature and density were conducted on KACST hybrid plasma source. The hybrid source involves ECR and helicon source operated simultanously. The results indicate that the ECR alone density is higher than the density of the combined sources while the combined temperature is lower.

GT1 77 MODELING AND SIMULATION

GT1 78 Simulation of Ion Energy and Angular Distribution Functions using a Multidimensional RF Sheath Model KAZUKI DENPOH, *Technology Development Center, Tokyo Electron Yamanashi Ltd.* We have developed a novel numerical tool to rapidly and precisely predict the ion energy and angular distribution functions (IEDF and IADF) for an rf sheath formed around an arbitrary surface geometry in a single- or dual-frequency capacitively coupled plasma (CCP). A Monte Carlo method coupled with our multidimensional rf sheath model [1] is utilized to simulate ion trajectories and collisions with neutrals in an oscillating sheath. The IEDF calculated for a one-dimensional sheath in a dual-frequency CCP agreed very well with data measured using the In-wafer Ion Energy Analyzer [2]. We also present the IEDF and IADF obtained for a two-dimensional sheath around a wafer edge and an adjacent focus ring in another dual-frequency CCP to demonstrate the multidimensional capability of the present model. The model should be of practical use for the research and development of semiconductor device manufacturing equipment.

[1]K. Denpoh and T. Shirafuji, Jpn. J. Appl. Phys. **50**, 036001 (2011).
[2]M. Funk *et al.*, presented at 59th Int. Symp. American Vacuum Soc., 2012.

GT1 79 Investigation of ion energy and angular distributions at the wafer edge in rf capacitively coupled reactors using CFD-ACE+ ANANTH BHOJ, ABHRA ROY, KUNAL JAIN, ZHONGMIN XIONG, *ESI Group* Dual frequency capacitively coupled reactors are now commonly used in microelectronics fabrication. The extent of possible independent control of ion fluxes and ion energy and angular distribution (IEADs) by varying HF and LF signals is currently a topic of great interest [1]. In this study, we report on investigations of IEADs in single and dual frequency CCPs, including the wafer edge refinement using CFD-ACE+. The current algorithms in CFD-ACE+ allow the determination of total power at the electrode or in the discharge. To account for the presence of two or more rf sources connected to a powered electrode, the existing numerical algorithms for power targeting were enhanced to track current at the electrode as a function of time, vary voltage and determine power as a function of frequency. The Monte Carlo transport module for heavy species in CFD-ACE+ was recently enhanced to compute IEADs in rf discharges. Results for the effect of varying power and pressure on IEADs were compared to semi-analytical models and data reported in Gahan *et al.* [1]. The validated model was applied to investigate the effect of details of HF and LF signals on IEADs in Argon discharges.

[1]Y. Zhang *et al.*, J. Vac. Sci. Technol. A **33**, 031302 (2015).
[2]D. Gahan *et al.*, Plasma Sources Sci. Technol. **21**, 024004 (2012).

GT1 80 Uniformity Control in Capacitively Coupled Plasmas SANG-HEON SONG, *TEL Technology Center, America, LLC.* PETER VENTZEK, *Tokyo Electron America* ALOK RANJAN, *TEL Technology Center, America, LLC.* In the fabrication of microelectronics devices, the volume production at mature yield is ultimately determined by the uniformity of the plasma. Plasma uniformity associated with patterning and hard mask open (HMO) steps are especially critical as the feature scale becomes smaller (<20 nm) than the limitation of ArF lithography. Capacitively coupled plasmas (CCP) are attractive for these processes as the uniformity of radical and ion fluxes onto the wafer can be made quite uniform. In the case of dual frequency CCP (DF-CCP) sources, the high frequency (HF) power may be applied to an upper electrode and low frequency (LF) power is applied to a lower electrode where a substrate is located. The upper electrode can be divided into inner and outer electrode segments in order to provide plasma uniformity control. In this presentation we describe the ion flux and energy distributions and radical flux to the substrate for a DF-CCP source generated using a 2-dimensional plasma hydrodynamics model. We compare simulated results with the experimental measurements. The ability to control the plasma uniformity is demonstrated showing how changing electrode gap distance and splitting power on the upper electrodes impacts species and energy flux to the substrate. Gap variations introduce trade-offs. We find that a more uniform ion flux can be obtained for smaller gaps. As we split the HF power more towards the outer electrode, the fluxes to the wafer becomes more uniform.

GT1 81 The effect of realistic energy dependent gamma-coefficients on heating dynamics and process control in capacitive radio frequency plasmas MANASWI DAKSHA, *West Virginia University* ARANKA DERZSI, IHOR KOROLOV, ZOLTAN DONKO, *Hungarian Academy of Sciences* EDMUND SCHUENGEL, JULIAN SCHULZE, *West Virginia University* In most PIC/MCC simulations of capacitively coupled plasmas (CCPs), only ion induced secondary electron emission from boundary surfaces is included. The corresponding emission probability, γ, is assumed to be constant and independent of the ion energy and surface conditions. It is usually guessed to be 0.1. However, in reality, γ-electron emission is known to be energy dependent and to be induced by fast atom impact and other processes, too. Here, we demonstrate that including realistic energy dependent γ-coefficients due to ion and fast atom impact strongly affects a variety of crucial plasma parameters under different discharge conditions: In single frequency

CCPs operated in Argon at 13.56 MHz, the plasma density, ion flux, and electron heating mode are found to be significantly affected by including realistic emission coefficients. In dual-frequency CCPs driven at 2 MHz and 27 MHz, the separate control of the mean ion energy and flux is demonstrated to be sensitive to a realistic modeling of secondary electron emission. By switching individual processes on and off in the simulation, we identify the dominant physical mechanisms causing these effects.

GT1 82 Particle-in-Cell Simulations of Atmospheric Pressure He/2%H2O Discharges* E. KAWAMURA, M.A. LIEBERMAN, A.J. LICHTENBERG, D.B. GRAVES, R. GOPALAKRISHNAN, *Univ of California - Berkeley* Atmospheric pressure micro-discharges in contact with liquid surfaces are of increasing interest, especially in the bio-medical field. We conduct 1D3v particle-in-cell (PIC) simulations of a voltage-driven 1 mm width atmospheric pressure He/2% H2O plasma discharge in series with an 0.5 mm width liquid H2O layer and a 1mm width quartz dielectric layer. A previously developed two-temperature hybrid global model of atmospheric pressure He/H2O discharges [1] was used to determine the most important species and collisional reactions to use in the PIC simulations. We found that H13O6+, H5O3−, and electrons were the most prominent charged species, while most of the metastable helium He* was quenched via Penning ionization. The ion-induced secondary emission coefficient γ_i was assumed to be 0.15 at all surfaces. A series of simulations were conducted at 27.12 MHz with $J_{rf} \approx$ 800–2200 A/m^2. The H2O rotational and vibrational excitation losses were so high that electrons reached the walls at thermal temperatures. We also simulated a much lower frequency case of 50 kHz with $V_{rf} = 10$ kV. In this case, the discharge ran in a pure time-varying γ-mode.

*This work was supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC0001939.

[1]Ke Ding, M. A. Lieberman, and A. J. Lichtenberg, J. Phys. D: Appl. Phys. **47**, 305203 (2014).

GT1 83 3D simulation of integrated multi-coil ICP source with azimuthal modes JOZEF BRCKA, *Tokyo Electron U.S. Holdings, Inc.* Integrated multi-coil (IMC) planar ICP source with azimuthal motion is presented. Scaling ICP sources to larger substrate size is always complicated due to many technical issues and is challenged by the plasma chemistry. The source described in this work has capability of azimuthally moving plasma and has potential for large area and high density plasma applications. Hence, this system does not have an ideal axial symmetry, the 3D model approach has to be used to assess its transient performance. Moreover, reactor walls are imposing stronger boundary conditions on distribution of the radicals in "off-axis reactive plasma." Intrinsic asymmetry of source and plasma were investigated by 3D fluid model developed under Plasma Module framework and supported by COMSOL Multiphysics solvers. Operation modes have potential to control plasma distribution, reaction chemistry and increase/modulate radicals' production. Simulation confirmed assumption that plasma distribution may essentially change in different gas. Under specific conditions integrated multi-coil ICP source is producing pulsed plasma. Temporal, spatial and population plasma characteristics were investigated in an inert carrier gas (Ar) and reactive plasma consisting of several gases (Ar, H2, CO and CH4).

GT1 84 Energy transfer model in non-equilibrium e-O2-O high temperature flows VINCENZO LAPORTA, *Ohio Aerospace Institute, Dayton 45431, Ohio* DOMENICO BRUNO, *Istituto di Nanotecnologia, CNR, 70126 Bari, Italy* ESWAR JOSYULA, *Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton 45433, Ohio* In the contribution to conference will be presented the first preliminary results of a kinetic model for the energy exchange in thermal and chemical non-equilibrium oxygen-containing high temperature flows.

GT1 85 Mobility of Ar$^+$ in CF$_4$ ZELJKA NIKITOVIC, VLADIMIR STOJANOVIC, ZORAN RASPOPOVIC, *Institute of Physics, University of Belgrade, Belgrade, Serbia* JASMINA JOVANOVIC, *Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia* ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Belgrade, Serbia* In this work we present a complete cross section set for Ar$^+$ in CF$_4$ where existing experimentally obtained data are selected and extrapolated. Monte Carlo simulation method is applied to accurately calculate transport parameters in hydrodynamic regime. We discuss new data for Ar$^+$ ions in CF$_4$ where flux and bulk values of reduced mobility are given as a function of E/N (E-electric field, N-gas density). We find that internally resonant exothermic dissociative charge transfer cross section for CF$_3^+$ production significantly increases zero field ion mobility with respect to the polarization limit.

GT1 86 Global model including multistep ionizations in helium plasmas SEUNGJU OH, HYO-CHANG LEE, CHIN-WOOK CHUNG, *Hanyang University* Particle and power balance equations including stepwise ionizations are derived and solved in helium plasma. In the balance equations, two metastable states (23S1 in singlet and 21S1 triplet) are considered and followings are obtained. The plasma density linearly increases and electron temperature is relatively in constant value against the absorbed power. It is also found that the contribution to multi-step ionization respect to the single-step ionization is in the range of 8% - 23%, as the gas pressure increases from 10 mTorr to 100 mTorr. There has little variation in the collisional energy loss per electron-ion pair created (Ec). These results indicate that the stepwise ionizations are the minor effect in case of the helium plasma compared to argon plasma. This is because that helium gas has very small collisional cross sections and higher inelastic collision threshold energy resulting in the little variations for the collisional energy loss per electron-ion pair created.

GT1 87 Computer simulation of charging effects in high aspect ratio structure JUN-HYEON MOON, HYUN-JU KANG, CHIN-WOOK CHUNG, *Hanyang University* As aspect ratio of semiconductor structure is increased, charging effect occurs in pattern etching process using plasma. To interpret the cause of the charging effect, simulation tool was used. The charges were accumulated in the trench wall and bottom by different motion of ions and electrons. The electric field in the trench changes the movement direction of positive ions, and then notching is occurred in bottom of the trench. Pulse source was applied to reduce the charging effect and it was interpreted in various conditions.

GT1 88 Simulating the charging of a particle on a surface in a plasma LUCAS HEIJMANS, SANDER NIJDAM, *Eindhoven University of Technology* It is common knowledge that a floating surface will charge negative when a plasma is applied over it. One can imagine that any macroscopic dust particle on the surface will also get charged. The theory that describes this charging is, however, underdeveloped. It has been suggested that the particle will share its charge with the surface, leading to roughly the same surface charge density. This is, however, only valid when both the surface and the particle are electrically conductive. In this contribution, we show a novel model to simulate the charge on a non-conducting particle on a surface in a plasma. It is based on balancing the ion and electron fluxes through the plasma sheath towards the particle. With this, we show that the charge on a particle on a surface can be five orders of magnitude higher than what was previously assumed. Knowledge of the charge on a particle on a surface is important, because it, combined with the plasma sheath electric field, will lead to an electric force on the particle. It has been proposed that this force is important in the lofting of dust from the surface of extra-terrestrial bodies. Additionally, it has been suggested, that it can be used for cleaning in high-tech applications, such as lithography machines and spacecrafts.

GT1 89 Coupling discharge and gas dynamics in streamer-less spark formation* ASHUTOSH AGNIHOTRI, *CWI Amsterdam* WILLEM HUNDSDORFER, *CWI Amsterdam and Radboud University, Nijmegen* UTE EBERT, *CWI Amsterdam and Eindhoven University of Technology, Eindhoven* We present simulations of streamer-less spark formation with a new 2D cylindrically symmetric model. The model incorporates the coupling between the electric discharge (described by a reaction-drift-diffusion model on the timescale of ion motion and Poisson's equation) and the gas (described by Euler equations and an energy balance equation for the heat generated). The model is employed to study electrical breakdown in supercritical N2 between planar electrodes under the application of pulsed voltages. We present the modeling results of gas heating by the electrical discharge and the back coupling of the thermally driven gas expansion on the discharge. Our model captures space-charge effects, thermal shocks and induced pressure waves. Because of secondary-electrode emission, we observe a cycle of electrons being released from the cathode, heating the gas, the gas affecting the discharge and the electrons being absorbed at the anode. This cycle might either lead to spark formation or to discharge decay.

*A. A. is supported by Dutch Physics funding agency, FOM, and Shell.

GT1 90 Conservation laws in embedding theory OSCAR MURILLO, ALEXANDER MUSTAFAEV, *National Mineral Resources University (Mining University)* In this work is considered embedding theory, a theory in which independent variables which describe gravity are functions of the space-time embedding into a ten-dimensional pseudo-Euclidean space. Neother's theorem is used to find conservation laws for energy and angular momentum as a result from the action's invariance in relation to the rotation and translation of the system. The form of these conservation laws and their consequences depending on the different formulations of embedding theory is discussed. It is also analyzed a transition from embedding theory to a field theory in a flat space-time with a number of dimensions greater than four. The same procedure is followed in this case to find conservation laws, resulting in the solution of the problem of time present in Einstein's theory of general relativity.

GT1 91 Numerical band structure calculations of plasma metamaterials DYLAN PEDERSON, KONSTANTINOS KOURTZANIDIS, LAXMINARAYAN RAJA, *The University of Texas at Austin* Metamaterials (MM) are materials engineered to display negative macroscopic permittivity and permeability. These materials allow for designed control over electromagnetic energy flow, especially at frequencies where natural materials do not interact. Plasmas have recently found application in MM as a negative permittivity component. The permittivity of a plasma depends on its electron density, which can be controlled by an applied field. This means that plasmas can be used in MM to actively control the transmission or reflection of incident waves. This work focuses on a plasma MM geometry in which microplasmas are generated in perforations in a metal plate. We characterizethis material by its band structure, which describes its interaction with incident waves. The plasma-EM interactions are obtained by coupling Maxwell's equations to a simplified plasma momentum equation. A plasma density profile is prescribed, and its effect on the band structure is investigated. The band structure calculations are typically done for static structures, whereas our current density responds to the incident waves. The resulting band structures are compared with experimental results.

GT1 92 Estimation of Photon Effects on Townsend Discharges for SecondaryElectronEmission Coefficient Measurements* TOMOKAZU YOSHINAGA, HARUAKI AKASHI, *National Defense Academy of Japan* A Monte Carlo simulation (MCS) is applied to investigate the secondary electron emission in Argon Townsend discharges. The influxes of ions, photons and metastable species onto the cathode surface are estimated simply from the number of inelastic collisions. The effect of photons becomes significant especially under higher pd conditions since the photon influx increases. This suggests the possibility of the estimation of the secondary electron emission coefficient of photons by examining breakdown voltage characteristics (Paschen curves). The effect of metastable species is much smaller than those of ions and photons and is negligible. The Paschen curves evaluated with MCS agrees well with the results of one-dimensional fluid model simulation when the photon effect is neglected, showing the necessity of further improvement.

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GT1 93 A Stabilization of LIBMESH Based Finite Element Method in Two-Dimensional Fluid Simulation of Capacitively Coupled Plasma HYONU CHANG, *Plasma Technology Research Center, National Fusion Research Institute* LIBMESH is a library for providing a framework for the numerical simulation of partial difference equations using arbitrary unstructured discretizations on serial and parallel platforms. A two-dimensional axisymmetric fluid simulation based on the finite element method which is supported by LIBMESH is introduced. Stabilization of this simulation is accomplished by using the test functions of Petrov-Galerkin scheme. An example of capacitively coupled plasma is modelled by the simulation and the results are compared with of other literatures.

GT1 94 A hybrid model in inductively coupled plasma discharges with bias source: Description of model and experimental validation in Ar discharge* DE-QI WEN, WEI LIU, YONG-XIN LIU, FEI GAO, YOU-NIAN WANG, *Dalian University of Technology* Traditional fluid simulation and Particle-in-Cell/Monte-Carlo collision (PIC/MCC) are very time consuming in inductively coupled plasma. In this work, a hybrid model, i.e. global model coupled bidirectional with parallel Monte-Carlo collision (MCC) sheath model, is developed to investigate inductively coupled plasma discharge with bias source. The global model is applied to calculate plasma density in bulk plasma. The sheath model is performed to consistently calculate the electric field, ion kinetic and the sheath thickness above the bias electrode. Moreover, specific numbers of ions are tracked and ultimately ion energy distribution functions (IEDFs) incident into bias electrode are obtained from MCC module. It is found that as the bias amplitude increases, the energy width of both IEDFs becomes wider, and the total outlines of IEDFs move towards higher energy. The results from the model are validated by experimental measurement and a qualitative agreement is obtained. The advantage of this model is that plasma density, ion flux and IEDF, which are widely concerned in the actual process, could be obtained within an hour.

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GT1 95 Hybrid Modeling of SiH_4/Ar Discharge in a Pulse Modulated RF Capacitively Coupled Plasma* WANG XI-FENG, SONG YUAN-HONG, WANG YOU-NIAN, *Dalin University of Technology* PSEG TEAM Pulsed plasmas have offered important advantages in future micro-devices, especially for electronegative gas plasmas. In this work, a one-dimensional fluid and Monte-Carlo (MC) hybrid model is developed to simulate SiH_4/Ar discharge in a pulse modulated radio-frequency (RF) capacitively coupled plasma (CCP). Time evolution densities of different species, such as electrons, ions, radicals, are calculated, as well as the electron energy probability function (EEPF) which is obtained by a MC simulation. By pulsing the RF source, the electron energy distributions and plasma properties can be modulated by pulse frequency and duty cycle. High electron energy tails are obtained during power-on period, with the SiHx densities increasing rapidly mainly by SiH_4 dissociation. As the RF power is off, the densities in the bulk region decrease rapidly owing to high energy electrons disappear, but increase near electrodes since diffusion without the confinement of high electric field, which can prolong the time of radials deposition on the plate. Especially, in the afterglow, the increase of negative ions near the electrodes results from cool electron attachment, which are good for film deposition.

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GT1 96 Radio-frequency breakdown in oxygen and synthetic air* ZORAN LJ PETROVIC, MARIJA SAVIC, MARIJA RADMILOVIC-RADJENOVIC, *Institute of Physics, Pregrevica 118 Zemun, University of Belgrade* Parallel plate rf discharges have a long history in the materials processing industry, but much of their behavior is still poorly understood, particularly processes taking place during the breakdown. In order to test some simple models of RF breakdown we have performed detailed simulations using well tested Monte Carlo code that allows also verification against RF and DC benchmarks but also treatment of temporal spatial non-localities. This work contains our simulation results of the breakdown voltage curves in oxygen and synthetic air. At first, electrons were released from the middle of the gap and any further development is due to the applied field, random number generator and solutions of kinetic and balance equations. The obtained results qualitatively agree with the existing experimental and simulation results. In addition, spatial distributions of electron concentration, energy and rates of elastic scattering and ionization are also presented and discussed in light of the processes leading to the breakdown. We analyze the role of low threshold inelastic collisions and non-conservative attachment as compared to the previous results for argon.

*Supported by MESTD projects ON171037 and III41011.

GT1 97 PlasmaPIC: A tool for modeling low-temperature plasma discharges* NINA SARAH MUEHLICH, MICHAEL BECKER, ROBERT HENRICH, CHRISTIAN HEILIGER, *Justus-Liebig-University Giessen, Institut fuer Theoretische Physik* PlasmaPIC is a three-dimensional particle in cell (PIC) code. It consists of an electrostatic part for modeling dc and rf-ccp discharges as well as an electrodynamic part for modeling inductively coupled discharges. The three-dimensional description enables the modeling of discharges in arbitrary geometries without limitations to any symmetry. These geometries can be easily imported from common CAD tools. A main feature of PlasmaPIC is the ability of an excellent massive parallelization of the computation, which scales linearly up to a few hundred cpu cores. This is achieved by using a multigrid algorithm for the field solver as well as an effective load balancing of the particles. Moreover, PlasmaPIC includes the interaction of the neutral gas and the plasma discharge. Because the neutral gas and the plasma simulation are acting on different time scales we perform the simulation of both separately in a self-consistent treatment, whereas the neutral gas distribution is calculated using the direct simulation Monte Carlo method (DSMC). The merge of these features turns PlasmaPIC into a powerful simulation tool for a wide range of plasma discharges and introduces a new way of understanding and optimizing low-temperature plasma applications.

*This work has been supported by the "Bundesministerium fuer Wirtschaft und Energie." Grant 50RS1507.

GT1 98 Verification of particle-in-cell simulations against exact solutions of kinetic equations* MILES TURNER, *Dublin City University* Demonstrating correctness of computer simulations (or verification) has become a matter of increasing concern in recent years. The strongest type of verification is a demonstration that the simulation converges to an exact solution of the mathematical model that is supposed to be solved. Of course, this is possible only if such an exact solution is available. In this paper, we are interested in kinetic simulation using the particle-in-cell method, and consequently a relevant exact solution must be a solution of a kinetic equation. While we know of no such solutions that exercise all the features of a typical particle-in-cell simulation, in this paper we show that the mathematical literature contains several such solutions that involve a large fraction of the functionality of such a code, and which collectively exercise essentially all of the code functionality. These solutions include the plane diode, the neutron criticality problem, and the calculation of ion energy distribution functions in oscillating fields. In each of theses cases, we can show the the particle-in-cell simulation converges to the exact solution in the expected way. These demonstrations are strong evidence of correct implementation.

*Work supported by Science Foundation Ireland under grant 08/SRC/I1411.

GT1 99 PLASIMO modelling of a helium atmospheric plasma jet DIANA MIHAILOVA, ANA SOBOTA, JAN VAN DIJK, *Eindhoven University of Technology* Atmospheric plasma jets are intensively studied because of their wide range of potential applications, in particular for surface treatments and in plasma medicine. The PLASIMO modeling toolkit is used to simulate the capillary plasma-jet in order to quantify the delivery of fluxes and fields to the treated sample. The setup under study consists of capillary powered electrode through which helium gas flows and a grounded ring electrode placed a distance of few mm in front of the capillary. The discharge is excited by sinusoidal voltage with amplitude of 2kV and 30KHz repetition rate. The plume emanating from the jet, or the plasma bullets, propagates through a Pyrex tube and the gas phase channel of helium exits into the surrounding air. The drift-diffusion module of PLASIMO is used to construct a model of the helium plasma jet with the aim to study the dynamics of the plasma inside and outside the source. We discuss the properties of the plasma source and the plasma plume or bullet emitted into the atmosphere. The modeling results are qualitatively compared with experimental observations.

GT1 100 A volume averaged global model for inductively coupled HBr/Ar plasma discharge SANG-YOUNG CHUNG, DEUK-CHUL KWON, HEECHOL CHOI, MI-YOUNG SONG, *National Fusion Research Institute* A global model for inductively coupled HBr/Ar plasma was developed. The model was based on a self-consistent global model had been developed by Kwon *et al.*, [1] and a set of chemical reactions in the HBr/Ar plasma was compiled by surveying theoretical, experimental and evaluative researches. In this model vibrational excitations of bi-atomic molecules and electronic excitations of hydrogen atom were taken into account. Neutralizations by collisions between positive and negative ions were considered with Hakman's approximate formula achieved by fitting of theoretical result. For some reactions that were not supplied from literatures the reaction parameters of Cl_2 and HCl were adopted as them Br_2 and HBr, respectively. For validation calculation results using this model were compared with experimental results from literatures for various plasma discharge parameters and it showed overall good agreement.

[1] J. Appl. Phys. **109**, 073311 (2011).

GT1 101 Spectral Kinetic Simulation of the Ideal Multipole Resonance Probe JUNBO GONG, SEBASTIAN WILCZEK, DANIEL SZEREMLEY, *Ruhr-University Bochum, Germany* JENS OBERRATH, *Leuphana University Lüneburg, Germany* DENIS EREMIN, *Ruhr-University Bochum, Germany* WLADISLAW DOBRYGIN, *Robert Bosch GmbH, Germany* CHRISTIAN SCHILLING, MICHAEL FRIEDRICHS, RALF PETER BRINKMANN, *Ruhr-University Bochum, Germany* The term Active Plasma Resonance Spectroscopy (APRS) denotes a class of diagnostic techniques which utilize the natural ability of plasmas to resonate on or near the electron plasma frequency ω_{pe}: An RF signal in the GHz range is coupled into the plasma via an electric probe; the spectral response of the plasma is recorded, and a mathematical model is used to determine plasma parameters such as the electron density ne or the electron temperature Te. One particular realization of the method is the Multipole Resonance Probe (MRP). The ideal MRP is a geometrically simplified version of that probe; it consists of two dielectrically shielded, hemispherical electrodes to which the RF signal is applied. A particle-based numerical algorithm is described which enables a kinetic simulation of the interaction of the probe with the plasma. Similar to the well-known particle-in-cell (PIC), it contains of two modules, a particle pusher and a field solver. The Poisson solver determines, with the help of a truncated expansion into spherical harmonics, the new electric field at each particle position directly without invoking a numerical grid. The effort of the scheme scales linearly with the ensemble size N.

GT1 102 The influence of electrohydrodynamic flow on the distribution of chemical species in positive corona* FRANCISCO PONTIGA, *University of Seville* KHELIFA YANALLAH, *University of Sheffield* R. BOUAZZA, *University of Tiaret* JUNHONG CHEN, *University of Wisconsin* A numerical simulation of positive corona discharge in air, including the effect of electrohydrodynamic (EHD) motion of the gas, has been carried out. Air flow is assumed to be confined between two parallel plates, and corona discharge is produced around a thin wire, midway between the plates. Therefore, fluid dynamics equations, including electrical forces, have been solved together with the continuity equation of each neutral species. The plasma chemical model included 24 chemical reactions and ten neutral species, in addition to electrons and positive ions. The results of the simulation have shown that the influence of EHD flow on the spatial distributions of the species is quite different depending on the species. Hence, reactive species like atomic oxygen and atomic nitrogen are confined to the vicinity of the wire, and they are weakly affected by the EHD gas motion. In contrast, nitrogen oxides and ozone are efficiently dragged outside the active region of the corona discharge by the EHD flow.

*This work was supported by the Spanish Government Agency "Ministerio de Ciencia e Innovación" under Contract No. FIS2011-25161.

GT1 103 3D PIC Modeling of Microcavity Discharge* MATTHEW HOPKINS, RONALD MANGINELL, CHRISTOPHER MOORE, BENJAMIN YEE, MATTHEW MOORMAN, *Sandia National Laboratories* We present a number of techniques and challenges in simulating the transient behavior of a microcavity discharge. Our microcavities are typically cylindrical with diameters approximately 50 - 100 μm, heights of 50 - 200 μm, pressure near atmospheric, and operate at a few hundred volts. We employ a fully kinetic simulation methodology, the Particle-in-Cell (PIC) method, with interparticle collisions handled via methods based on direct simulation Monte Carlo (DSMC). In particular, we explicitly include kinetic electrons. Some of the challenges we encounter include variations in number densities, external circuit coupling, and time step resolution constraints. By employing dynamic particle weighting (particle weights vary over time by species and location) we can mitigate some of the challenges modeling systems with 10^7 variations in number densities. Smoothing mechanisms have been used to attempt to mitigate external circuit response. We perform our simulations on hundreds or thousands of processing cores to accommodate the computational work inherent in using relatively small time step sizes (e.g., 50 fs for a 100 ns calculation). In addition, particle weighting issues inherent to three-dimensional low temperature plasma systems will be mentioned.

*Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's NNSA under Contract DE-AC04-94AL85000.

GT1 104 GLOWS: DC, PULSED, MICROWAVE, OTHERS

GT1 105 Generation of Diffuse Large Volume Plasma by an Ionization Wave from a Plasma Jet MOUNIR LAROUSSI, HAMID RAZAVI, *Old Dominion University* Low temperature plasma jets emitted in ambient air are the product of fast ionization waves that are guided within a channel of a gas flow, such as helium. This guided ionization wave can be transmitted through a dielectric material and under some conditions can ignite a discharge behind the dielectric material. Here we present a novel way to produce large volume diffuse low pressure plasma inside a Pyrex chamber that does not have any electrodes or electrical energy directly applied to it. The diffuse plasma is ignited inside the chamber by a plasma jet located externally to the chamber and that is physically and electrically unconnected to the chamber. Instead, the plasma jet is just brought in close proximity to the external wall/surface of the chamber or to a dielectric tubing connected to the chamber. The plasma thus generated is diffuse, large volume and with physical and chemical characteristics that are different than the external plasma jet that ignited it. So by using a plasma jet we are able to "remotely" ignite volumetric plasma under controlled conditions. This novel method of "remote" generation of a low pressure, low temperature diffuse plasma can be useful for various applications including material processing and biomedicine.

GT1 106 Microwave Plasma Excitation Using Cylindrical Cavity with Dual Injection YUICHI HASEGAWA, KEIJI NAKAMURA, *Chubu University* SOONAM PARK, SATORU KOBAYASHI, *Applied Materials* HIDEO SUGAI, *Nagoya Industrial Science Research Institute* CHUBU UNIVERSITY TEAM, APPLIED MATERIALS TEAM, NAGOYA INDUSTRIAL SCIENCE RESEARCH INSTITUTE TEAM Large high-density plasmas have been generated by injecting magnetron-based microwaves radiated from slots cut on a wall of a rectangular or coaxial waveguide. However, a standing structural microwave in the waveguide often causes non-uniformity of plasma density. To minimize such inhomogeneity excited by the conventional waveguide, we adopt a resonant cylindrical cavity combined with a solid-state microwave amplifier. Microwave is injected into the cavity from two ports azimuthally apart by 90 degrees to each other (*dual injection*). FDTD simulations are performed for a TE_{111} mode resonant cavity excited by *single* or *dual* microwave injection. In the case of the dual injection with a phase difference of $\pi/2$, the wave field azimuthally rotates in the cavity, and hence the slots cut on a cavity bottom wall launch travelling waves, thus minimizing the azimuthal inhomogeneity of the resultant plasma. 40-cm-diameter plasmas are experimentally generated in argon at $0.1 \sim 5$ Torr with microwaves of 2.4–2.5GHz and 400W. Threshold powers for plasma ignition are much less in *dual* injection than those in *single* injection. Optical emission images of the cylindrical plasmas show that the plasma uniformity is considerably improved in *dual* injection, particularly at high-pressure and low-power.

GT1 107 Time evolution of the plasma column structure and gas temperature in pulsed surface wave discharges produced at microwave frequencies in helium at intermediate pressure JOELLE MARGOT, FABRICE VALADE, AHMAD HAMDAN, *University of Montreal* FRANCOIS VIDAL, JEAN-PIERRE MATTE, *INRS* Pulsed surface wave discharges produced at microwave frequency in helium at intermediate pressure (1-50 Torr) were investigated. The time-evolution of the spatial structure of the plasma column was studied by using iCCD imaging. An ionization front is observed that propagates with a typical velocity of a few km/s soon after plasma ignition and decreases rapidly afterwards until the plasma reaches its steady state. A "plasma bullet" of a few cm long is also observed several tens of microseconds after breakdown especially at lower pressure. On the other hand, by using the rotational structure of OH molecular band emission, the gas temperature was determined as a function of time at different axial positions. Depending on the operating conditions, its value is typically in the range 400-900° C. It is also found that the gas temperature reaches its steady-state value within a few hundreds of microseconds after ignition and that it decreases as the plasma columns expands.

GT1 108 Positive column of the glow discharge in argon VALERIY LISOVSKIY,* EKATERINA ARTUSHENKO, VLADIMIR YEGORENKOV, *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine* We report the measurements we performed of the reduced electric field strength E/p in the positive column in the range of the gas pressure and tube radius product of $0.01 < pR < 30$ Torr·cm. We got good agreements with numerical models and experimental data of other authors. We also present two analytical models for the reduced electric field E/p. The first model deals with the ambipolar mode of the positive column of the constant current discharge in noble gases. We consider the case of a balance between the rate of charged particle production due to direct ionization of gas molecules through electron impact and their escape to the discharge tube walls. Simple expressions for the reduced electric field E/p in the positive column in argon are obtained. The second model consists in considering the production and loss of charged particles and metastable atoms and obtaining a simple equation for the reduced electric field E/p depending on the discharge current density, gas pressure and tube radius. These models furnish a good description of experimental data in the whole range of pR values studied.

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GT1 109 Mechanisms of gas breakdown in non-uniform electric field between flat electrodes VALERIY LISOVSKIY,* RUSLAN OSMAYEV, VLADIMIR YEGORENKOV, *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine* This paper studies how the electric field non-uniformity and the electron diffusion escape affect the DC gas breakdown between flat electrodes. We registered the breakdown curves of the DC discharge between the electrodes having the radius of $R_e = 6$ mm with the inter-electrode gap values L between 3 and 72 mm in the tubes of inner diameter values of 13 and 56 mm within the nitrogen pressure range p from 0.02 to 120 Torr. We found that the breakdown curves for the gap of 3 mm actually match in the total pressure range, the diffusion escape of electrons to the tube walls playing no role in the gas breakdown process. In a narrow tube the minimum breakdown voltage is constant in the range of $L/R_e \leqslant 1$ but with the subsequent gap growth it increases linearly in order to compensate for the diffusion loss to the tube walls. For the wide tubes of 56 mm in diameter and for the gap of 72 mm the breakdown curves possess more flat minima and they run in the range of lower breakdown voltage values than one for a narrow tube. The minimum breakdown voltage grows slowly only in the range of $L/R_e > 2$.

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GT1 110 Modes of burning and axial structure of dc discharge with transverse diaphragm POLINA OGLOBLINA, VALERIY LISOVSKIY,* VLADIMIR YEGORENKOV, *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine* This paper reports the CVCs of the dc discharge with a diaphragm located between the electrodes. We determined the conditions when normal and abnormal modes of such a dc discharge can exist. The axial profiles of the plasma parameters (electron temperature, plasma potential and concentration) from the anode to the cathode sheath boundary were also registered with a single Langmuir probe. We demonstrated that at low nitrogen pressure of 0.1 Torr and the discharge current of 1 mA a double layer was formed near the diaphragm only in the cathode part of the tube whereas with the current of 10 mA the double layer expanded to the anode part too. At the nitrogen pressure of 0.5 Torr a positive column was observed in the anode part of the tube, and the double layers were formed on both sides of the diaphragm (in the anode as well as in the cathode parts of the tube). These layers accelerated electrons into the orifice.

In all cases the maximum of the plasma concentration is located inside the orifice.

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GT1 111 PLASMA APPLICATIONS

GT1 112 Plasma Discharge Effect on Secondary Electron Yield of Various Surface Locations on SRF Cavities MILOS BASOVIC, *Old Dominion University, Center for Accelerator Science* ANA SAMOLOV, FILIP CUCKOV, *University of Massachusetts Boston, Engineering Department* MILETA TOMOVIC, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Old Dominion University, Center for Accelerator Science* Electron activity (field emission and multipacting) has been identified as the main limiting factor of Superconducting Radiofrequency (SRF) cavity performance. Secondary Electron Yield (SEY) is highly dependent on the state of the cavity's surface, which is investigated before and after plasma exposure. Current methods for simulating the electron activity in SRF cavity consider it as a uniform surface. Due to fabricating procedure there are three distinct areas of the cavity's microstructure: weld zone, heat affected zone, and base metal zone. Each zone has a characteristic microstructure even after the treatments that are currently used to clean the surface of the cavities. Improvement of existing surface treatment techniques, or use of a new is required in order to increase the limit of Q factor towards the theoretical limit of Nb. RF discharge is a promising technique for this purpose. In order to test the effect of the plasma on the SEY of the various cavity surface zones we have developed the experimental setup to measure the energy distribution of the SEY from coupon-like samples. Samples are made in a way that all three zones of cavity surface will be included in the examination. We will present the SEY changes in these three zones before and after plasma treatment.

GT1 113 Three Modes of Air Atmospheric Pressure Plasma ABDEL-ALEAM H. MOHAMED, *Taibah University* Atmospheric pressure plasma jet operating in air have gained a high interest due to its various applications in industry and biomedical [1]. The presented air plasma jet system is consisted of stainless steel hollow needle electrode of 1 mm inner diameter which is covered with a quartz tube with a 1 mm diameter side hole. The hole is above the tube nozzle by 5 mm and it is covered by a copper ring which is connected to the ground. The needle is connected to sinusoidal 27 kHz high voltage power supply (25 kV) though a current limiting resistor of 50 kΩ. The tested distance between the needle tip and the side hole was 1 mm or 2.1 mm gape. The electric and plasma jet formation characteristics show three modes of operations. Through these modes the plasma length changes with air flow rate to increase in the first mode and to confine inside the quartz tube in the second mode, then it start to eject from the nozzle again and increase with flow rate to reach a maximum length of 7 mm at 4.5 SLM air flow rate in the third mode. The measured gas temperature of the plasma jet can approach room temperature (300 K). Moreover, the plasma jet emission spectra shows the presence of reactive O and OH radical in the plasma jet. These results indicate that the generated air plasma jet can be used a plasma sterilization.

[1]A.-A. H. Mohamed, J. F. Kolb, and Schoenbach, Eur. Phys. J. D **60**, 517 (2010).

GT1 114 Optical Emission Spectroscopy in PECVD Helps Modulate Key Features in Biofunctional Coatings for Medical Implants MIGUEL SANTOS, PRAVEESUDA MICHAEL, ELYSSE FILIPE, *PhD student* STEVEN WISE, *Postdoctoral Scientist* MARCELA BILEK, *Professor* THE UNIVERSITY OF SYDNEY COLLABORATION, THE HEART RESEARCH INSTITUTE COLLABORATION We explore the use of optical emission spectroscopy (OES) diagnostic tools as a process feedback control strategy in plasma-assisted deposition of biofunctional coatings. Hydrogenated carbon nitride coatings are deposited on medical-grade metallic substrates using radio-frequency (rf) discharges sustained in $C_2H_2/N_2/Ar$ gaseous mixtures. The discharge is generated by capacitively coupling the rf power (supplied at $f = 13.56$ MHz) to the plasma and the substrates are electrically biased using a pulse generator to provide microsecond square profiled pulses at voltages in the range $|V_{bias}| = 250$ V – 1000 V. Nitrogen content and CN bonding configurations in the coatings follow similar trends to those of CN radicals and nitrogen molecular ions in the discharge. OES is used as a non-intrusive diagnostic technique to identify a suitable window of process parameters and ultimately achieve biofunctional interfaces compatible with current clinical demands. Importantly, we demonstrate that key features of the coatings can be modulated and made suitable for blood and/or tissue contacting medical implants, such as coronary stents and orthopaedic implants. The coatings are mechanically robust, inherently non-thrombogenic and can be readily modified, enabling an easy functionalization through the immobilization of biological molecules in a bioactive conformation.

GT1 115 Development of Simplified Atmospheric-Pressure Plasma Nitriding HIROFUMI YAMAMOTO, RYUTA ICHIKI, AKIHIDE MAEDA, KENTA YAMANOUCHI, SHUICHI AKAMINE, SEIJI KANAZAWA, *Oita University* OITA UNIVERSITY TEAM Nitriding treatment is one of the surface hardening technologies, applied to dies and automobile components. In recent industry, low-pressure nitriding treatment using vacuum system is mainstream. On the other hand, we have originally developed an atmospheric-pressure plasma nitriding which do not need vacuum system. However we needed an air-tight container to purge residual oxygen and external heater to control treatment temperature. To make this technique practical, we addressed to construct a simplified treatment system, where treatment temperature is controlled by thermal plasma itself and oxygen purging is achieved by a simple cover. This means that any air-tight container and external heater is not necessary. As a result, surface temperature is controlled by changing treatment gap from nozzle tip to steel surface. We succeeded in controlling well thickness of hardened layer by adjusting treatment temperature even in such a simplified system. In the conference, we also discuss experimental results for hardening complex shaped materials by using our simplified nitriding.

GT1 116 Sterilization Efficiency of Spore forming Bacteria in Powdery Food by Atmospheric Pressure Plasmas Sterilizer MASAYOSHI NAGATA, MASASHI TANAKA, YUSUKE KIKUCHI, *University of Hyogo* To provide food sterilization method capable of killing highly heat resistant spore forming bacteria, we have studied effects of plasma treatment method at atmospheric pressure in order to develop a new high speed plasma sterilization apparatus with a low cost and a high efficiency. It is also difficult even for the plasma treatment to sterilize powdery food including spices such as soybean, basil and turmeric. This paper describes that an introduction of mechanical rotation of a treatment space increases the efficiency so that perfect inactivation of spore forming bacteria in these materials by a short treatment time has been demonstrated in our experiments. We also will discuss the sterilization mechanism by dielectric barrier discharge.

GT1 117 Development of High-Density Plasma Photonic Crystals Using High-Power Lasers* ROBERTO COLON QUINONES, BENJAMIN WANG, ANDREA LUCCA FABRIS, MARK CAPPELLI, *Stanford University* A plasma photonic crystal (PPC) is an array of plasma structures that interacts with electromagnetic (EM) waves in ways not possible with natural materials. 2D PPCs can be used for generating a band gap, which is a range of wave frequencies in which no waves are transmitted through the structure. Such gap forms when an EM wave travels through a 2D PPC with spacing equal to half the wavelength of the wave and plasma frequency (ω_p) on the order of the frequency of the wave. Until recently, research on PPCs has been limited to $\omega_p < 30$ GHz, which is equivalent to a plasma density of $n_e < 10^{13}\text{cm}^{-3}$. Over the last year, PPCs of $n_e > 10^{15}\text{cm}^{-3}$ have been generated at Stanford through the use of high-power lasers. The PPCs are generated by expanding the laser beam from a Q-switched Nd:YAG laser through a Galilean beam expander and subsequently focusing the beam through an optical micro-lens array. The intense photoionization of air that occurs at the focus of the individual lenses leads to the formation of a 2D array of very dense plasma spots. Photomultiplier measurements show a plasma lifetime of ~150 ns during which the plasma array functions as a PPC, representing a first step towards advancing the field forward into the low THz regime.

*Sponsored by the AFOSR MURI and DoD NDSEG.

GT1 118 Fast Rise Time and High Voltage Nanosecond Pulses at High Pulse Repetition Frequency* KENNETH E. MILLER, TIMOTHY ZIEMBA, JAMES PRAGER, JULIAN PICARD, AKEL HASHIM, *Eagle Harbor Technologies, Inc.* Eagle Harbor Technologies (EHT), Inc. is conducting research to decrease the rise time and increase the output voltage of the EHT Nanosecond Pulser product line, which allows for independently, user-adjustable output voltage (0 – 20 kV), pulse width (20 – 500 ns), and pulse repetition frequency (0 – 100 kHz). The goals are to develop higher voltage pulses (50 – 60 kV), decrease the rise time from 20 to below 10 ns, and maintain the high pulse repetition capabilities. These new capabilities have applications to pseudospark generation, corona production, liquid discharges, and nonlinear transmission line driving for microwave production.

*This work is supported in part by the US Navy SBIR program.

GT1 119 Analysis and utilization of plasma treated water for food and agricultural interest SANGHOO PARK, YOUBONG LIM, JOO YOUNG PARK, WONHO CHOE, *Korea Advanced Institute of Science and Technology* HYUN-JOO KIM, HAE IN YONG, CHEORUN JO, *Seoul National University* SAMOOEL JUNG, *Chungnam National University* Attention on aqueous chemical species produced in plasma-treated solutions through plasma-liquid interactions has been increased because of its strong relation to bio/medical and food applications. The long-lived and reactive oxygen and nitrogen species such as hydrogen peroxide, ozone, superoxide anion, and oxyacids play a crucial role in those applications. The plasma treatment brings about absorption of these species into the target liquid and also induces changes in liquid characteristics and composition via photolysis by plasma UV emission and post-discharge reactions. In this presentation, we discuss the result of our investigation of the chemical properties related to the two main oxyacids, HNO_2 and HNO_3, in plasma treated water (PTW). Water was treated in close proximity by our SDBD system developed specifically to meet the application requirements. The chemical properties of the solution varied gradually over the treatment time and storage time. Here we report the result of our experiment, theoretical analysis, and their consistency. Furthermore, the dependence of the nitrite ion production yield on the dissipated power, treatment time, and dielectric material will be discussed. Based on the revealed fundamental characteristics, the utilization of PTW in the meat curing process as one of the nitrite sources will be briefly demonstrated. In terms of sausage quality, there were no noticeable effects of PTW on the total aerobic bacteria counts, color, and peroxide values of sausages compared with those using celery powder and sodium nitrite.

GT1 120 Magnetic and structural properties of $CaMn_{0.9}Mo_{0.1}O_3$ perovskite synthesized in abnormal glow discharge ARMANDO SARMIENTO SANTOS, CARLOS ARTURO PARRA VARGAS, IVAN SUPELANO GARCÍA, *GSEC-Universidad Pedagógica y Tecnológica de Colombia* In this work we use the abnormal glow discharge (AGD) to produce the $CaMn_{0.9}Mo_{0.1}O_3$ perovskite through decarbonize, calcination and sintering steps. Structural characterization was carry out by Rietveld refinement of X-ray diffraction on samples after sintering step. The magnetic properties was analysed through magnetization curves as a function of temperature for applied magnetic fields in the range of 20 Oe to 20 kOe by the ZFC-FC method and magnetization curves in function of the applied field at 50 K and 300 K temperatures. The $CaMn_{0.9}Mo_{0.1}O_3$ perovskite was also produced by conventional method in resistive furnace and its behaviour was compared with those of the plasma synthesized. The X-ray analysis reveals that the samples produced by both methods crystalized in a Pnma structure, the lattice parameters change and one second phase appears when the AGD is applied in the last production steps. The magnetization measurements allow analysing the behaviour of the sample at low temperatures and comparing the magnetic transitions in the samples produced by both methods; these are influenced according to production method employed. The results shows that the use of AGD is an alternative method to produce ceramic materials, which reduced ostensibly the production time and allow to obtain similar magnetic and structural properties with respect to conventional method.

GT1 121 PLASMAS FOR LIGHT PRODUCTION: LASER MEDIA, GLOWS, ARCS, FLAT PANELS AND NOVEL SOURCES

GT1 122 Effects of Plasma Formation on the Cesium Diode (DPAL) and Excimer (XPAL) Pumped Alkali Laser* ARAM H. MARKOSYAN, MARK J. KUSHNER, *University of Michigan* Diode pumped alkali lasers (DPALs) and excimer pumped alkali lasers (XPALs) are being investigated as a means to convert optical pumps having poor optical quality to laser radiation having high optical quality [1]. DPALs sustained in Cs vapor are pumped on the D_2(852.35 nm), $Cs(6^2S_{1/2}) \rightarrow Cs(6^2P_{3/2})$, transition and lase on the D_1(894.59 nm) transition, $Cs(6^2P_{1/2}) \rightarrow Cs(6^2S_{1/2})$. Collisional mixing (spin orbit relaxation) of the $Cs(6^2P_{3/2})$ and $Cs(6^2P_{1/2})$ levels is a key part of this three-level (in fact, a quasi-two-level) laser scheme. In the five-level XPAL pumping scheme, the $CsAr(B^2\Sigma^+_{1/2})$ state is optically pumped by 836.7 nm pulses, which later dissociates and produces $Cs(6^2P_{3/2})$. As in DPAL, a collisional relaxant transfers the population of $Cs(6^2P_{3/2})$ to $Cs(6^2P_{1/2})$, which enables lasing on D_1 transition. A first principals global computer model has been developed for both systems to investigate the effects of plasma formation on the laser performance. Argon is used as a buffer gas and nitrogen or ethane are used as a collisional relaxant at total pressure of 600 Torr at temperatures of 350-450 K, which produces vapor pressures of Cs of <0.1 Torr. In both systems, a plasma formation in excess of 10^{14} - 10^{16}cm^{-3} occurs, which potentially reduces laser output power by electron collisional mixing of upper and lower laser levels [2].

*Work supported by DoD High Energy Laser Multidisc, Res. Initiative.

[1]W. F. Krupke *et al.*, Opt. Lett. **28**, 2336 (2003).
[2]B. D. Barmashenko *et al.*, Opt. Comm. **292**, 123 (2013).

GT1 123 Ultraviolet Light Source Using Electrodeless Microwave Discharge TAKU NISHIKAWA, *Nagoya Univ.* HIROTAKA TOYODA, *Nagoya Univ., PLANT, Nagoya Univ.* Surface treatment technologies using ultraviolet (UV) light, such as organic residue removal, surface modification or sterilization, are widely used. So far, UV lamps using DC discharge with electrodes inside the lamp tube is commonly used. However, sputtering of electrode materials sometimes causes deposition on the inner tube surface as well as degradation of the electrodes, resulting in short life time of the lamp tube. In this study, we propose an electrodeless UV mercury (Hg) lamp source using microwave power. 2.45 GHz Microwave power (<4 kW) from a power supply is divided into four power lines using branch waveguides. A mercury lamp tube (diameter: 9.6 mm, length: 42 cm, Hg: 13.5 mg, Ar: 1 Torr) is inserted into the branch waveguides and microwave power is coupled to the plasma. Emission from the lamp is monitored by a monochromator and an 254 nm UV monitor. Lamp temperature is also measured by a thermography camera and tube temperature up to 900 K with good uniformity along ~ 30 cm was observed. Uniformity of the 254 nm UV light intensity was +15 % along the lamp tube. The maximum UV light intensity of 64 mW/cm^2 was observed at a microwave power of 4 kW.

GT1 124 EUV nanosecond laser ablation of silicon carbide, tungsten and molybdenum* OLEKSANDR FROLOV, KAREL KOLACEK, JIRI SCHMIDT, JAROSLAV STRAUS, *Pulse Plasma Systems Department, Institute of Plasma Physics AS CR, v.v.i., Prague, 182 00, Czech Republic* ANDREI CHOUKOUROV, *Department of Macromolecular Physics, Faculty of Mathematics and Physics, Charles University in Prague, Prague, 121 16, Czech Republic* KOICHI KASUYA, *Institute of Applied Flow, 3-24-4 Utsukushigaoka-Nishi, Aoba, Yokohama, Kanagawa 225-0001, Japan* In this paper we present results of study interaction of nanosecond EUV laser pulses at wavelength of 46.9 nm with silicon carbide (SiC), tungsten (W) and molybdenum (Mo). As a source of laser radiation was used discharge-plasma driver CAPEX (CAPillary EXperiment) based on high current capillary discharge in argon. The laser beam is focused with a spherical Si/Sc multilayer-coated mirror on samples. Experimental study has been performed with 1, 5, 10, 20 and 50 laser pulses ablation of SiC, W and Mo at various fluence values. Firstly, sample surface modification in the nanosecond time scale have been registered by optical microscope. And the secondly, laser beam footprints on the samples have been analyzed by atomic-force microscope (AFM).

*This work supported by the Czech Science Foundation under Contract GA14-29772S and by the Grant Agency of the Ministry of Education, Youth and Sports of the Czech Republic under Contract LG13029.

GT1 125 Radiative properties of Ceramic Metal-Halide High Intensity Discharge lamps (CMH) containing additives in argon plasma YANN CRESSAULT, PHILIPPE TEULET, GEORGES ZISSIS, *Toulouse* LAPLACE TEAM The lighting represents a consumption of about 19% of the world electricity production. We are thus searching new effective and environment-friendlier light sources. The Ceramic Metal-Halide High Intensity Lamps (CMH) are one of the options for illuminating very high area. The new CMH lamps are mercury free and contain additives species which lead to a richer spectrum in specific spectral intervals, a better colour temperature or colour rendering index. This work is particularly focused on the power radiated by these lamps, estimated using the Net Emission Coefficient, and depending on several additives (calcium, sodium, tungsten, dysprosium, thallium or strontium).

GT1 126 Time resolved EUV spectra from Zpinching capillary discharge plasma* ALEXANDR JANCAREK, MICHAL NEVRKLA, FAHAD NAWAZ, *Czech Technical University in Prague* We developed [1] symmetrically charged driver to obtain high voltage, high current Z-pinching capillary discharge. Plasma is created by up to 70 kA, 29 ns risetime current pulse passing through a 5 mm inner diameter, 224 mm long capillary filled with gas to initial pressure in the range of 1 kPa. Due to the low inductance design of the driver, the pinch is observable directly from the measured current curve. Time-integrated and time-resolved spectra of discharge plasma radiation are recorded together with the capillary current and analyzed. The most encouraging spectra were captured in the wavelength range 8.3 ÷ 14 nm. This spectral region contains nitrogen Balmer series lines including potentially lasing NVII 2 – 3 transition. Spectral lines are identified in the NIST database using the FLY kinetic code. The line of 13.38 nm wavelength, transition NVII 2 – 3, was observed in gated, and also in time-integrated spectra for currents >60 kA.

*This work has been supported by the Ministry of Education, Youth and Sports of the Czech Republic grants LG13029.

[1]M. Nevrkla, A. Jancarek, and F. Nawaz, Discharge driver for 13.4 nm XUV laser, 2013 19th IEEE Pulsed Power Conference, PPC 2013; San Francisco, CA; United States; 16 June 2013 through 21 June 2013; Code 101034

GT1 127 Spectroscopic studies of Cr VI species in a laser produced plasma* NICOLAI KLEMKE, SMIJESH NADARAJAN, DANE LABAN, JAMES WOOD, DASHAVIR CHETTY, DAVID KIELPINSKI, IGOR LITVINYUK, ROBERT SANG, *Australian Attosecond Science Facility, Centre for Quantum Dynamics, Griffith University* We present measurements characterizing a laser generated, highly ionized microplasma suitable to extend the cut-off energy of High Harmonic Generation (HHG) to energies up to 5 keV. The HHG process occurs when a strong ultrafast laser hits a gaseous target producing coherent radiation with a much higher photon energy than the driving laser. Commonly, noble gases are used and typical photon energies of several 100 eV are obtained. We plan to use Cr^{5+} species as the target for HHG as generated by a double pulse method: the first pulse creates the plasma, the second pulse is used to obtain the temperature required for Cr^{5+}. Here, we present results on the optimization of plasma parameters such as the plasma temperature, the number density and the dynamics of Cr^{5+} by means of spectroscopic techniques in the optical and the XUV regime.

*This research is supported by Lockheed Martin and the Australian Research Council.

GT1 128 Temperature Dependence of Nitro-Quenching by Atmospheric-Pressure Plasma MASAKI MITANI, RYUTA ICHIKI, YUTARO IWAKIRI, SHUICHI AKAMINE, SEIJI KANAZAWA, *Oita University* A lot of techniques exist as the hardening method of steels, such as nitriding, carburizing and quenching. However, low-alloy steels cannot be hardened by nitriding because hardening by nitriding requires nitride precipitates of special alloy elements such as rare metals. Recently, nitro-quenching (NQ) was developed as a new hardening process, where nitrogen invokes martensitic transformation instead of carbon. NQ is adaptable to hardening low-alloy steels because it does not require alloy elements. In industrial NQ, nitrogen diffusion into steel surface is operated in high temperature ammonia gas. As a new technology, we have developed surface hardening of low-alloy steel by NQ using an atmospheric-pressure plasma. Here the pulsed-arc plasma jet with nitrogen/hydrogen gas mixture is sprayed onto steel surface and then water quench the sample. As a result, the surface of low-alloy steel was partially hardened up to 800 Hv by producing iron-nitrogen martensite. However, the hardness profile is considerably non-uniform. We found that the non-uniform hardness profile can be controlled by changing the treatment gap, the gap between the jet nozzle and the sample surface. Eventually, we succeeded in hardening a targeted part of steel by optimizing the treatment gap. Moreover, we propose the mechanism of non-uniform hardness.

GT1 129 A Kinetic Plasma-Pumped Rare Gas Laser* GUY PARSEY, *Michigan State University* YAMAN GÜÇLÜ, *Max Planck Institute* JOHN VERBONCOEUR, ANDREW CHRISTLIEB, *Michigan State University* Extending from diode-pumped alkali vapor lasers (DPAL), Han and Heaven [1] have shown that rare gas metastable states, $np^5(n+1)s[3/2]_2$, can operate as the base of a three-level laser with excition of the $(n+1)s \rightarrow (n+1)p$ transitions. Though both the rare gas lasers (RGL) and DPALs can be excited with incoherent optical pumping, RGLs do not suffer from the highly reactive behavior of alkali metals. Since metastable populations are maintained via electric discharge, we propose using a tuned electron energy distribution function (EEDF) to modify RGL efficiencies and drive the population inversion. The EEDF is maintained by the discharge along with the introduction of electron sources. Using our kinetic global modeling framework (KGMf) and three gas systems (helium buffered argon and krypton along with pure argon), we first validate the intracavity intensity laser model and then generate gain and energy efficiency baselines for each system. Parameter scanning methods are then used to find optimized EEDFs and system parameters for metastable production, generation of a lasing population inversion, and increasing RGL operation efficiencies. Finally, we determine if an RGL can operate without optical pumping.

*Supported by AFOSR and a MSU Strategic Partnership Grant

[1]Han and Heaven, Opt. Lett. **37**, 2157.

GT1 130 PLASMA ETCHING

GT1 131 Atomic layer etching of SiO_2 under Ar/ C_4F_8 plasmas with pulsed bias* SAI-QIAN ZHANG, ZHONG-LING DAI,† YOU-NIAN WANG, *School of Physics and Optoelectronic Engineering, Dalian University of Technology* PLASMA SIMULATION AND EXPERIMENT GROUP (PSEG) TEAM The purge steps in the atomic layer etching (ALE) reduce the throughput and increase the costs. By elaborately choosing bias pulse waveforms, ALE can be achieved without alternating feedstock gas, although compromises are needed between throughput and precision. In this study, a multi-scale model is used to simulate ALE of SiO_2 with a pulsed bias in Ar/C_4F_8 plasmas. Firstly, a commercial software CFD-ACE+ is used to calculate the reactant fluxes towards the substrate in a CCP reactor. The ion bombardment energy and angular distributions at substrate are calculated with a hybrid sheath model, where electric field is got from fluid equations, and the ion-neutral collisions are considered applying the Monte Carlo(MC) method. Then, the reactant transport and surface MC reaction algorithm are coupled in a feature scale model. Influences of bias pulse frequency and duty ratio on atomic precision control are studied. Also, comparisons are made between conventional ALE and pulsed bias etching. Results show that when pulsed bias is used instead of alternating the feedstock gas, we can still achieve certain self-limiting nature in etching, with higher throughput and acceptable loss of precision.

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GT1 132 Many flaked particles generated by electric field stress working as an impulsive force in mass-production plasma etching equipment* YUJI KASASHIMA, FUMIHIKO UESUGI, *National Institute of Advanced Industrial Science and Technology (AIST)* Particles generated in plasma etching significantly lower production yield. In plasma etching, etching reaction products adhere to the inner chamber walls, gradually forming films, and particles are generated by flaking of the deposited films due to electric field stress that acts boundary between the inner wall and the film. In this study, we have investigated the mechanism of instantaneous generation of many flaked particles using the mass-production reactive ion etching equipment. Particles, which flake off from the films on the ground electrode, are detected by the in-situ particle monitoring system using a sheet-shaped laser beam. The results indicate that the deposited films are severely damaged and flake off as numerous particles when the floating potential at the inner wall suddenly changes. This is because the rapid change in floating potential, observed when unusual wafer movement and micro-arc discharge occur, causes electric field stress working as an impulsive force. The films are easily detached by the impulsive force and many flaked particles are instantaneously generated. This mechanism can occur on not only a ground electrode but a chamber walls, and cause serious contamination in mass-production line.

*This work was partially supported by JSPS KAKENHI Grant Number B 26870903.

GT1 133 Plasma discharge characteristics in compact SF_6 radio-frequency plasma source for plasma etching application TAISEI MOTOMURA, *AIST* KAZUNORI TAKAHASHI, *Tohoku Univ.* YUJI KASASHIMA, FUMIHIKO UESUGI, *AIST* AKIRA ANDO, *Tohoku Univ.* In order to create a compact plasma etching reactor, plasma discharge characteristics in compact SF_6 radio-frequency (RF) plasma source which has a chamber diameter of 40 mm have been studied. Convergent magnetic field configuration produced by a solenoid coil and a permanent magnet located behind substrate is employed for efficient plasma transport downstream of plasma source. A discharge characteristics with the changes in relative emission intensity of fluorine atom of FI at 703.7 nm in compact SF_6 plasma source are discussed: the dependence of relative emission intensity on the magnetic field strength, the RF input power, and the mass flow rate of the SF_6 gas. The relative emission intensity was significantly increased when the RF input power is ~150 W. We present the fundamental etching performance (especially etching rate) of compact plasma source, and then the etching rate of 0.1-1.0 μm/min was obtained under the condition of a RF input power of 50-200 W, a mass flow rate of SF_6 of 5.5 sccm and a bias RF power of 20 W. The results of test etching will be shown in presentation.

GT1 134 Study on the decontamination of surface of radioactive metal device using plasmatron JONG-KEUN YANG, IK-JUN YANG, SEUNG-HYEON KIM, SURESH RAI, HEON-JU LEE, *Jeju National University* NUCLEAR FUSION AND PLASMA APPLICATION LABORATORY TEAM Radioactive waste contiguously produced during operation of NPP (nuclear power plant). Therefore, KHNP (korea hydro & nuclear power co., ltd) decided to disband the NPP unit 1 in the Kori area. Since most of the metallic radioactive wastes are not contaminated ones themselves but rather ones containing polluted nuclides on their surface, the amount of wastes can be sharply reduced through decontamination process. In this study DC plasmatron and isotope sheet of radioactive cobalt was used to study the decontamination process. Decontamination can be achieved by etching the contaminated layer from the surface. Due to the restricted usage of radioactive materials, we have studied etching of Cobalt (Co) sheet to imitate the radioactive contamination. Plasma was generated using mixture gas of CF4/O2 in the ratio of 10:0, 9:1, 8:2, 7:3, 6:4 maintaining the plasma sample distance of 20 mm, 30 mm, 40 mm and exposed time of 60 sec, 120 sec, 180 sec using fixed Ar carrier gas flow rate of 1000 sccm. As a result, we obtained maximum etching rate of 9.24 μm/min when the mixture ratio of CF4/O2 gas was 4:1, which was confirmed by SEM and mass-meter. It was confirmed that more close positioning the Co samples to the plasmatron nozzle yields maximum etching rate.

GT1 135 A new method of dry cleaning after plasma etching of MRAM materials TAKUYA KUBO,* SONG-YUN KANG, *Tokyo Electron Ltd.* TOKYO ELECTRON LTD. TEAM This paper describes a new method for dry cleaning after etching of MRAM materials. Problems such as repeatability or particle generation after etching of MRAM materials are due to the non-volatile nature of etch products. A new etch concept for MRAM is to etch each material such as carbon, metal, or silicon compounds step by step. There are 4 steps in this cleaning: 1) carbon removal by N2/H2, 2) metal removal by Ar, 3) silicon removal by CF4/O2, 4) carbon, oxygen, and fluorine removal by N2/H2. Etch repeatability and particle level reduction have been demonstrated to result from this cleaning method.

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GT1 136 PLASMA DEPOSITION

GT1 137 Antifouling Transparent ZnO Thin Films Fabricated by Atmospheric Pressure Cold Plasma Deposition YOSHIFUMI SUZAKI, *Professor, Faculty of Engineering, Kagawa University* JINLONG DU, *Graduate School of Engineering, Kagawa University* TOSHIFUMI YUJI, *Faculty of Education & Culture, University of Miyazaki* HAYATO MIYAGAWA, KAZUFUMI OGAWA, *Faculty of Engineering, Kagawa University* One problem with outdoor-mounted solar panels is that power generation efficiency is reduced by face plate dirt; a problem with electronic touch panels is the deterioration of screen visibility caused by finger grease stains. To solve these problems, we should fabricate antifouling surfaces which have superhydrophobic and oil-repellent properties without spoiling the transparency of the transparent substrate. In this study, an antifouling surface with both superhydrophobicity and oil-repellency was fabricated on a glass substrate by forming a fractal microstructure. The fractal microstructure was constituted of transparent silica particles 100 nm in diameter and transparent zinc-oxide columns grown on silica particles through atmospheric pressure cold plasma deposition; the sample surface was coated with a chemically adsorbed monomolecular layer. Samples were obtained which had a superhydrophobic property (with a water droplet contact angle of more than 150°) and a high average transmittance of about 90% (with wavelengths ranging from 400 nm to 780 nm).

GT1 138 New Method for Production of High-Energy Neutral Molecules of Reactive Gases* ALEXANDER METEL, VASILY BOLBUKOV, MARINA VOLOSOVA, SERGEI GRIGORIEV, YURY MELNIK, *Moscow State University of Technology "STANKIN"* For the surface modification of dielectric substrates by reactive gas molecules with energy of 100 keV they are usually produced due to charge exchange collisions of ions extracted from a plasma emitter and accelerated by high-voltage pulses. As generation of the ion plasma emitter at a 100-kV potential is quite difficult, it was proposed to extract the ions from a ground potential emitter, accelerate them by high voltage between the emitter and a negatively biased high-transparency grid and transform them into fast neutral molecules in the positive space charge sheaths of the grid. As the energy of fast molecules is defined by potentials of charge exchange collision points inside the sheath their spectrum ranges from zero to a value corresponding to the pulse amplitude. A reverse beam is always generated due to acceleration of ions from the plasma on the other side of the grid. The lower the latter density, the higher the ratio of the primary to the reverse beam currents. When the grid is composed of parallel flat plates, the charge exchange due to reflections from the plates substantially contributes at low gas pressure to production of molecules with the energy corresponding to the pulse amplitude.

*The work was supported by the Grant No. 14-29-00297 of the Russian Science Foundation.

GT1 139 Effects of sputtering mode on the microstructure and ionic conductivity of yttria-stabilized zirconia films T.H. YEH, R.D. LIN, B.R. CHERNG, J.S. CHERNG, *Ming Chi University of Technology* The microstructure and ionic conductivity of reactively sputtered yttria-stabilized zirconia (YSZ) films in various sputtering modes are systematically studied using a closed-loop controlled system with plasma emission monitoring. A transition-mode sputtering corresponding to 45% of target poisoning produces a microstructure with ultrafine crystallites embedded in an amorphous matrix, which undergoes an abnormal grain growth upon annealing at 800°C. At 400°C, its measured ionic conductivity is higher, by about a half order of magnitude, than that of its 86%-target-poisoning counterpart, which is in turn higher than the YSZ bulk by about one order of magnitude. The abnormally-grown ultra-large grain size is believed to be responsible for the former comparison due to the suppression of the grain boundary blocking effect, while the latter comparison can be attributed to the interface effect.

GT1 140 Preparation of hydrogenated diamond-like carbon films by reactive Ar/CH_4 high power impulse magnetron sputtering with negative pulse voltage* TAKASHI KIMURA, HIKARU KAMATA, *Nagoya Institute of Technology* High power impulse magnetron sputtering (HiPIMS) has been attracted, because sputtered target species are highly ionized. High densities of active species such as radical ions and neutral radicals can be also achieved owing to high density reactive HiPIMS plasmas. We investigate properties of hydrogenated diamond-like carbon films prepared by reactive HiPIMS of Ar/CH_4 gas mixture. The properties of the films strongly depend on the plasma compositions and the kinetic energy of the carbon-containing ions which can enter into the films. The film preparation is performed at an average power of 60 W and a repetition frequency of 110 Hz, changing CH_4 fraction up to 15%. Total pressure ranges between 0.3 and 2 Pa. The maximum of instantaneous power is about 20-25 kW, and the magnitude of the current is 36 A. A negative pulse voltage is applied to the substrates for about 10 μs after the target voltage changed from about -600 V to 0 V. The structural properties are characterized by Raman spectroscopy and nano-indentation method. Film hardness strongly depends on the magnitude of negative pulse voltage. By adjusting the magnitude of negative voltage, the film hardness ranges between about 10 and 22 GPa.

*This work is partially supported by JSPS KAKENHI Grant Number 26420230.

GT1 141 Formation of hydrogenated amorphous carbon films by reactive high power impulse magnetron sputtering containing C_2H_2 gas* TAKASHI KIMURA, HIKARU KAMATA, *Nagoya Institute of Technology* Diamond-like carbon (DLC) films have attracted interest for material industries, because they have unique properties. Hydrogenated amorphous carbon films are prepared by reactive high power impulse magnetron sputtering (HiPIMS) containing C_2H_2 gas and the properties of the films produced in Ar/C_2H_2 and Ne/C_2H_2 HiPIMS are compared. Production of hydrocarbon radicals and their ions strongly depends on both electron temperature and electron density in HiPIMS. Therefore, the influence of the difference in buffer gas (Ar and Ne) on the film properties is also valuable to investigate. The film preparation is performed at an average power of 60 W and a repetition frequency of 110 Hz. Total pressure ranges between 0.3 and 2 Pa. The maximum of instantaneous power is about 20-25 kW, and the magnitude of the current is 35 A. A negative pulse voltage is applied to the substrates for about 15 μs after the target voltage changed from about -500 V to 0 V. Hardness of the films prepared by Ar/C_2H_2 HiPIMS monotonically decreases with increasing the total pressure, whereas that of the films prepared by Ne/C_2H_2 HiPIMS does not strongly depend on the total pressure.

*This work is partially supported by JSPS KAKENHI Grant Number 26420230.

GT1 142 Open Air Silicon Deposition by Atmospheric Pressure Plasma under Local Ambient Gas Control* TERUKI NAITO, NOBUAKI KONNO, YUKIHISA YOSHIDA, *Mitsubishi Electric Corporation* In this paper, we report open air silicon (Si) deposition by combining a silane free Si deposition technology and a newly developed local ambient gas control technology. Recently, material processing in open air has been investigated intensively. While a variety of materials have been deposited, there were only few reports on Si deposition due to the susceptibility to contamination and the hazardous nature of source materials. Since Si deposition is one of the most important processes in device fabrication, we have developed open air silicon deposition technologies in BEANS project. For a clean and safe process, a local ambient gas control head was designed. Process gas leakage was prevented by local evacuation, and air contamination was shut out by inert curtain gas. By numerical and experimental investigations, a safe and clean process condition with air contamination less than 10 ppm was achieved. Si film was deposited in open air by atmospheric pressure plasma enhanced chemical transport under the local ambient gas control. The film was microcrystalline Si with the crystallite size of 17 nm, and the Hall mobility was 2.3 $cm^2/V \cdot s$. These properties were comparable to those of Si films deposited in a vacuum chamber.

*This research has been conducted as one of the research items of New Energy and Industrial Technology Development Organization "BEANS" project.

GT1 143 PECVD of SiOC Films Using a Sheet-type Atmospheric Pressure Plasma Jet KOUTA NAKAJIMA, KENJI TANAKA, TATSURU SHIRAFUJI, *Osaka City University* Packaging industries have used SiOC thin films for gas barrier coatings on the membranes for packaging foods, drug, and so on. PECVD is the most extensively employed method for preparing the SiOC films. However, PECVD is a process performed at a low pressure in general and requires expensive vacuum systems, especially in the case of large area coatings. Atmospheric pressure PECVD is a candidate to overcome this issue. If we simply apply atmospheric pressure plasma to CVD processes, however, we will encounter the problem of particle formation because of the high collision frequency in the environment of atmospheric pressure. In this work, we have developed a reactor that utilizes a unique gas-flow scheme for avoiding the particle formation. We have successfully deposited SiOC films by using this reactor, in which the source material is hexamethyldisiloxane and discharge/carrier gas is He. XPS measurements on the SiOC films have revealed that the films contain relatively higher concentrations of unfavorable methyl groups that reduce gas barrier performances. However, no particulates are involved in and on the deposited films as long as characterizing the films with eye observation and with transmission electron microscopy.

GT1 144 Effect of Low-Energy Ions on Plasma-Enhanced Deposition of Cubic Boron Nitride* M. TORIGOE, S. FUKUI, K. TEII, S. MATSUMOTO, *Kyushu University* The effect of low-energy ions on deposition of cubic boron nitride (cBN) films in an inductively coupled plasma with the chemistry of fluorine is studied in terms of ion energy, ion flux, and ion to boron flux ratio onto the substrate [1]. The ion energy and the ion to boron flux ratio are determined from the sheath potential and the ratio of incident ion flux to net deposited boron flux, respectively. For negative substrate biases where sp^2-bonded BN phase only or no deposit is formed, both the ion energy and the ion to boron flux ratio are high. For positive substrate biases where cBN phase is formed, the ion energy and the ion to boron flux ratio are estimated in the range of a few eV to 35 eV and 100 to 130, respectively. The impact of negative ions is presumed to be negligible due to their low kinetic energy relative to the sheath potential over the substrate surface. The impact of positive ions with high ion to boron flux ratios is primarily responsible for reduction of the ion energy for cBN film deposition.

*Work supported in part by a Grant-in-Aid for Scientific Research (B), a Funding Program for Next Generation World-Leading Researchers, and an Industrial Technology Research Grant Program 2008.

[1]K. Teii and S. Matsumoto, Thin Solid Films **576**, 50 (2015).

GT1 145 Raman Spectroscopy of *a*-C:H Films Deposited Using Ar + H_2+ C_7H_8 Plasma CVD XIAO DONG, KAZUNORI KOGA, DAISUKE YAMASHITA, HYUNWOONG SEO, NAHO ITAGAKI, MASAHARU SHIRATANI, *Kyushu University* YUICHI SETSUHARA, *Osaka University* MAKOTO SEKINE, MASARU HORI, *Nagoya University* We investigated the effects of ion energy on Raman spectra of a-C:H films prepared by Ar + H_2+ C_7H_8 plasma CVD. Raman spectra were measured with a laser Raman spectrometer (JASCO NRS-3100). Both the D-peak position and G-peak position shift toward higher wavenumbers as ion energy increases. The intensity ratio of the D-peak and G-peak, I_D/I_G increases with increasing the ion energy, indicating that the amount of ring-like sp^2 clusters increases. The H content in a-C:H derived from photoluminescence (PL) background decreases with increasing the ion energy. The full width at half maximum of the G-peak, $FWHM_G$ related to the C-C sp^3 content and H content increases with increasing the ion energy to 100 eV, whereas it decreases with increasing further the ion energy to 105 eV. The variation of $FWHM_G$ is consistent with that of mass density. There results indicate that the structure of a-C:H films transforms from polymer-like carbon to diamond-like one with increasing the ion energy above the threshold value of $\sim$ 100 eV.

GT1 146 Preparation of mixed metal thin films by a PVD method using several kinds of powder targets YOSHIAKI SUDA, HIROHARU KAWASAKI, TAMIKO OHSHIMA, YOSHIHITO YAGYU, TAKESHI IHARA, MAKIKO YAMAUCHI, *National Institute of Technology, Sasebo College* PLASMA PROCESS AND APPLICATION TEAM Bismuth iron garnet ($Bi_3Fe_5O_{12}$) and aluminum doped zinc oxide (AZO) thin films were prepared by a physical vapor deposition method using mixed metal powder targets. The X-ray powder diffraction and X-ray photoelectron spectroscopy results suggest that crystalline thin films can be prepared using powder targets with quality similar to that of the films prepared using bulk targets. $Bi_3Fe_5O_{12}$ films prepared using the pulsed laser deposition method were Bi rich, which may be due to the lower melting temperature of Bi (544 K) compared with that of Fe (1811 K). The mean transparency and resistivity of the AZO films prepared by the sputtering method were approximately 79%–84% and 0.5−1.4 ohm/cm, respectively.

GT1 147 Plasma-Enhanced Deposition of Nanocrystalline Diamond/Carbon Nanowall Composite Films for Field Emitters K. TEII, Y. KANEKO, K. TERADA, *Kyushu University* A.T.H. CHUANG, *University of Cambridge* Two methods of substrate scratching pretreatment using diamond powder are employed to fabricate nanocrystalline diamond/carbon nanowall (CNW) composite films [1]. The surface after scraping for undulation has continuous undulant scratches with a number of residual diamond grains exclusively along the scratches, while that after scratching with ultrasonic vibration shows irregular distributions of residual diamond grains and scratches, depending upon the size of the powder. Nanocrystalline diamond film/CNW composites are obtained with either pretreatment method by moderate-pressure microwave plasma-enhanced chemical vapor deposition using an $Ar/N_2/CH_4$ mixture. With increasing the duration of scratching, the morphology of the deposits changes from CNWs to a film/CNW composite and lastly to CNWs on a film, accompanied by an overall increase in wall spacing. The turn-on field for field emission decreases from 2.1 V/μm without scratching down to 1.2 V/μm with scratching due to suppression of electric field screening between the walls as evidenced by the larger field enhancement factor.

[1] C. Y. Cheng, M. Nakashima, K. Teii, Diamond Relat. Mater. **27-28**, 40 (2012).

GT1 148 New barrierless copper-alloy film for future applications CHON-HSIN LIN LIN, *Asia-Pacific Institute of Creativity* Since Cu metallization results in a conductivity and an electromigration resistance greater than those of Al, it has become popular for making Si-based interconnects for numerous devices in the field of microelectronics. Following the current trend of miniaturization required for most electronic components, there is a greater need for further size reduction in Si-based devices. The most critical side effect of size reduction is the increase in electronic scattering and resistivity when the barrier-layer thickness is further reduced. To explore advanced Cu-metallization methods and to develop a more economical manufacturing process for Cu-alloy films, the development of Cu materials having better quality and higher thermal stability becomes imperative for the metallization and annealing processes. For this purpose, we first fabricated Cu(GeNx) films and examined their thermal stability and electrical reliability after either cyclic or isothermal annealing. The excellent thermal and electrical properties make these new Cu-alloy films highly promising for applications that require more reliable and inexpensive copper interconnects. In this study, we fabricated Cu alloy films by doping a minute amount of Ge or GeNx, respectively, into the Cu films via barrierless Cu metallization, an inexpensive manufacturing method. Using these newly fabricated alloy films, we were able to eliminate or at least substantially reduce the detrimental interaction between the alloy and the barrierless Si substrate. The Cu(GeNx) films also exhibited high thermal stability, low resistivity and leakage current, and long time-dependent dielectric breakdown (TDDB) lifetimes, making such novel films a candidate for high-quality, economical, and more reliable Cu interconnects.

GT1 149 Substrate temperature dependence of Au-induced crystalline Ge film formation using sputtering deposition SOTA TANAMI, DAIKI ICHIDA, SHINJI HASHIMOTO, *Kyushu University* GIICHIRO UCHIDA, *Osaka Univesity* HYUNWOONG SEO, DAISUKE YAMASHITA, KAZUNIHIRO KAMATAKI, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* We are developing Au-induced crystalline Ge film formation using sputtering deposition. For the method, very thin Au films were deposited on SiO_2 substrates and then Ge atoms were irradiated to the Au films by sputtering. We found two kinds of Ge film growth: one is Ge film formation on Au films, and the other is Ge film formed between Au films and SiO_2. The latter film formation, however, takes place in a narrow temperature range around 140°C. Here we report two kinds of substrate temperature dependence of Ge film formation: one is annealing temperature of Au films, and the other is the substrate temperature dependence during Ge sputtering. 30nm-thick Au films were deposited quartz glass as a catalyst at room temperature by sputtering. Then the Au films were annealed in a temperature range from room temperature to 190 °C in a vacuum. Au grain grows and crystal orientation shows better alignment as the annealing temperature rises. We found that the smaller grain size with random orientation is better for Ge film formed between Au films and SiO_2.

GT1 150 Measurements of nitrogen atom density in N2/Ar sputtering plasma for fabrication of high-mobility amorphous In2O3:Sn films TOSHIYUKI TAKASAKI, TOMOAKI IDE, KOICHI MATSUSHIMA, *Kyushu University* KEIGO TAKEDA, MASARU HORI, *Nagoya University* DAISUKE YAMASHITA, HYUMWOON SEO, KAZUNORI KOGA, MASAHARU SHIRATANI, NAHO ITAGAKI, *Kyushu University* Amorphous In2O3:Sn (a-ITO) has attracted attention because of the advantages such as smooth surface and high etching rate. We have recently succeeded in sputtering deposition of a-ITO films with high mobility 61 cm^2/Vs by introducing N2 into the deposition atmosphere. Here, aiming to clarify effects of N of a-ITO film growth, we measure absolute density of N atom in N2/Ar sputtering plasma by using vacuum UV absorption spectroscopy. ITO films were fabricated by RF magnetron sputtering on glass substrates at 150C with Ar-N2 mixed gas. We observed that the morphology is changed from polycrystalline to amorphous by introducing N2 into the deposition atmosphere. Furthermore the mobility of a-ITO films was found to be greatly dependent on N2 flow rate. The electron Hall mobility increases from 48 to 55 cm^2/Vs with increasing N2 flow rate ratio from 3 to 5%, where the absolute density of N atom in the plasma increases from 3.78 to 7.44 (10^{10} cm^{-3}). Since the N composition ratio in ITO films is almost constant for N2 flow rate ratio of 3–5%, the difference in the adsorption/desorption behavior of N atoms on the growth surface brings about the change in the film properties.

GT1 151 Magnetic properties of $Fe/FeSi_2/Fe_3Si$ trilayered films prepared by facing targets sputtering deposition* KAZUYA ISHIBASHI, KAZUTOSHI NAKASHIMA, *Department of Applied Science for Electronics and Materials, Kyushu University* KEN-ICHIRO SAKAI, *Department of Control and Information Systems Engineering, Kurume National College of Technology* TSUYOSHI YOSHITAKE, *Department of Applied Science for Electronics and Materials, Kyushu University* Whereas giant magnetoresistance and tunnel magnetoresistance films generally employ nonmagnetic metal and insulator spacers, respectively, we have studied $Fe_3Si/FeSi$ artificial lattices, in which $FeSi_2$ is semiconducting and its employment as spacers is specific to our research. For the formation of parallel/antiparallel alignments of layer magnetizations, the employment of ferromagnetic layers with different coercive forces is required. There have been few studies on the fabrication of Fe-Si system spin valves comprising ferromagnetic layers with different coercive forces. In this work, Fe_3Si and Fe were employed as ferromagnetic layer materials with different coercive forces. $Fe/FeSi_2/Fe_3Si$ trilayered spin valve junctions by facing targets direct-current sputtering deposition combined with a mask method, and their electrical and magnetic properties were studied. An Fe_3Si layer was epitaxially grown on Si(111) substrate as a bottom layer. After that, An Fe layer with a large coercive force was deposited as a top layer, posterior to a $FeSi_2$ layer being deposited. From magnetization curves measured by a vibrating sample magnetometer, it was confirmed that the parallel and antiparallel magnetization alignments of ferromagnetic layers are clearly realized.

*This work was supported by JSPS KAKENHI Grant Number 15K21594.

GT1 152 Cluster Incorporation into A-Si:H Films Deposited Using H_2+SiH_4 Discharge Plasmas* SUSUMU TOKO, YOSHIHIRO TORIGOE, KIMITAKA KEYA, HYUNWOONG SEO, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu Univ.* Light-induced degradation is the most important issue for hydrogenated amorphous silicon (a-Si:H) solar cells. Our previous results have suggested that incorporation of clusters into films is responsible for the light-induced degradation. Therefore, it is important to control the incorporation of clusters. Recently, we have developed multi-hollow discharge plasma CVD method, by which clusters are driven toward the downstream region and high quality a-Si:H films can be deposited in the upstream region [1]. Here, we report effects of H_2 dilution on cluster incorporation. Cluster size was measured by TEM, and the incorporation amount of clusters was measured with quartz crystal microbalances [2]. H_2 dilution leads to smaller clusters and the cluster incorporation in the upstream region increases with H_2 dilution because the diffusion velocity of such small clusters much surpasses gas flow velocity.

*This work was partly supported by NEDO, PVTEC, and KAKENHI Grant Number 15J05441.

[1]K. Koga *et al.*, Jpn. J. Appl. Phys. **44**, L1430 (2005).
[2]Y. Kim *et al.*, Jpn. J. Appl. Phys. **52**, 01AD01 (2013).

GT1 153 Development of DLC cone for fast ignition experiment* MAYUKO KOGA, TAKUMA ONO, TAKUMA TOKUNAGA, *University of Hyogo* HAYATO KADOTA, TAKASHI HASHIMOTO, *Osaka University* KAZUHIRO KANDA, *University of Hyogo* TAKAYOSHI NORIMATSU, *Osaka University* In fast ignition research, a divergence of laser-generated hot electrons is a serious problem. Using DLC cones is one of actions against this problem. However, it is difficult to make a stand alone DLC cone because it needs a thick DLC layer. In this reserch, we studied preparation conditions for thick DLC layers and characteristics of DLC layers. We prepared a DLC layer on a brass conical bar by using a plasma-based ion implantation and deposition (PBIID) system. Acetylene gas or toluene vapor was used as a source. It was found that low gas pressure and low RF pulse power is suitable for thick DLC layer deposition. It was found that the toluene vapor had an advantage in thick layer deposition because of its high deposition rate. These DLC layers showed SP3 rich property in Near edge X-ray absorption fine structures (NEXAFS) spectra. Based on these results, we succeeded in making stand alone DLC cones.

*This work was supported by JSPS KAKENHI Grant Number 26420853 and Collaboration Research Program by NIFS (NIFS12KUGK063).

GT1 154 Measurements of absolute densities of nitrogen and oxygen atoms in sputtering plasma for fabrication of ZnInON films KOICHI MATSUSHIMA, TOMOAKI IDE, *Kyushu University* KEIGO TAKEDA, MASARU HORI, *Nagoya University* DAISUKE YAMASHITA, HYUNWOONG SEO, KAZUNORI KOGA, MASAHARU SHIRATANI, NAHO ITAGAKI, *Kyushu University* Control of chemical composition in films is of great importance in controlling the physical properties. Recently, we have developed ZnInON (ZION) with tunable band gap over the entire visible spectrum [1]. Due to the deviation from its pseudo-stoichiometry ($(ZnO)_x(InN)_{1-x}$), however, the films have a number of crystal defects. In this study, with the aim of precise control of the chemical composition, we have measured absolute densities of N and O in sputtering plasma during deposition. ZION films were deposited with Ar/N2/O2 gas mixtures. The absolute densities of N and O were measured by vacuum ultraviolet absorption spectroscopy. With increasing O2/N2 flow rate ratio from 0 to 15%, N density increases from 2.7 to 9.7×10^{11} cm^{-3}, while O density is almost constant with the value of 4.5×10^{11} cm^{-3}. These results indicate that incorporation of O atoms into ZION films increases with increasing the O2 flow rate ratio. Furthermore, we found that ZION films with pseudo-stoichiometric composition are grown at the O_2/N_2 flow rate ratio of 15%, where ZION films have low defect density.

[1]N. Itagaki *et al.*, Mater. Res. Express **1**, 036405 (2014).

GT1 155 Measurement of absolute density of N atom in sputtering plasma for epitaxial growth ZnO films via nitrogen mediated crystallization* TOMOAKI IDE, KOICHI MATSUSHIMA, TOSHIYUKI TAKASAKI, *Kyushu University* KEIGO TAKEDA, MASARU HORI, *Nagoya University* DAISUKE YAMASHITA, HYUWOONG SEO, KAZUNORI KOGA, MASAHARU SHIRATANI, NAHO ITAGAKI, *Kyushu University* ZnO has attracted attention as a potential alternative to GaN in light emitting diodes because of the wide band gap and large exciton binding energy. Recently, we have developed a fabrication method of ZnO by sputtering, nitrogen mediated crystallization (NMC), enabling us to make epitaxial films with low defect density. By utilizing the buffer layers fabricated by NMC method, we have succeeded in fabrication of single crystalline ZnO films even on 18% lattice mismatched substrates. Here, aiming to clarify effects of nitrogen during NMC process, we measured absolute density of N atom in sputtering plasma by means of vacuum ultra violet absorption spectroscopy. First, NMC–ZnO buffer layers were deposited in Ar/N2 atmosphere. Then, ZnO films were deposited in Ar/O2 atmosphere. With increasing N2 flow rate ratio from 4 to 12%, the N density increases from 3.2×10^{10} to 1.4×10^{11} cm^{-3}. By utilizing the NMC–ZnO buffer layer fabricated at under these conditions, single crystalline ZnO films are grown. However, large number of pits are observed on the surface of ZnO films under N-rich conditions, indicating that N density is of importance in controlling the morphology of ZnO films.

*This work was supported in part by Japan Society for the Promotion of Science KAKENHI Grant Number 15H05431.

GT1 156 Plasma-Assisted Mist Chemical Vapor Deposition of Zinc Oxide Films for Flexible Electronics* KOSUKE TAKENAKA, GIICHIRO UCHIDA, YUICHI SETSUHARA, *Osaka University* Plasma-assisted mist chemical vapor deposition of ZnO films was performed for transparent conductive oxide formation of flexible electronics. In this study, ZnO films deposition using atmospheric-pressure He plasma generated by a micro-hollow cathode-type plasma source has been demonstrated. To obtain detail information according to generation of species in the plasma, the optical emission spectra of the atmospheric pressure He plasma with and without mist were measured. The result without mist shows considerable emissions of He lines, emissions attributed to the excitation and dissociation of air including N_2 and O_2 (N, O, and NO radials, and N_2 molecule; N_2 second positive band and first positive band), while the results with mist showed strong emissions attributed to the dissociation of H_2O (OH and H radicals). The deposition of ZnO films was performed using atmospheric-pressure He plasma. The XRD patterns showed no crystallization of the ZnO films irradiated with pure He. On the other hand, the ZnO film crystallized with the irradiation with He/O_2 mixture plasma. These results indicate that the atmospheric-pressure He/O_2 mixture plasma has sufficient reactivity necessary for the crystallization of ZnO films at room temperature.

*This work was supported partly by The Grant-in-Aid for Scientific Research (KAKENHI) (Grant-in-Aid for Scientific Research(C)) from the Japan Society for the Promotion of Science (JSPS).

GT1 157 Laser-induced metal plasmas for pulsed laser deposition of metal-oxide thin films* ERIK WAGENAARS, *York Plasma Institute, University of York, UK* JAMES COLGAN, *Los Alamos National Laboratory, USA* SUDHA RAJENDIRAN, ANDREW ROSSALL, *York Plasma Institute, University of York, UK* Metal and metal-oxide thin films, e.g. ZnO, MgO, Al_2O_3 and TiO_2, are widely used in e.g. microelectronics, catalysts, photonics and displays. Pulsed Laser Deposition (PLD) is a plasma-based thin-film deposition technique that is highly versatile and fast, however it suffers from limitations in control of film quality due to a lack of fundamental understanding of the underlying physical processes. We present experimental and modelling studies of the initial phases of PLD: laser ablation and plume expansion. A 2D hydrodynamic code, POLLUX, is used to model the laser-solid interaction of a Zn ablation with a Nd:YAG laser. In this early phase of PLD, the plasma plume has temperatures of about 10 eV, is highly ionized, and travels with a velocity of about 10-100 km/sec away from the target. Subsequently, the plasma enters the plume expansion phase in which the plasma cools down and collision chemistry changes the composition of the plume. Time-integrated optical emission spectroscopy shows that Zn I and Zn II emission lines dominate the visible range of the light emission. Comparison with the Los Alamos plasma kinetics code ATOMIC shows an average temperature around 1 eV, indicating a significant drop in plasma temperature during the expansion phase.

*We acknowledge support from the UK Engineering and Physical Sciences Research Council (EPSRC), Grant EP/K018388/1.

GT1 158 Plasma polymerization for cell adhesive/anti-adhesive implant coating* JUERGEN MEICHSNER, *University of Greifswald* HOLGER TESTRICH, *INP Greifswald* HENRIKE REBL, BARBARA NEBE, *University of Rostock* Plasma polymerization of ethylenediamine ($C_2H_8N_2$, EDA) and perfluoropropane (C_3F_8, PFP) with admixture of argon and hydrogen, respectively, was studied using an asymmetric 13.56 MHz CCP. The analysis of the plasma chemical gas phase processes for stable molecules revealed consecutive reactions: $C_2H_8N_2$ consumption, intermediate product NH_3, and main final product HCN. In C_3F_8-H_2 plasma the precursor molecule C_3F_8 and molecular hydrogen are consumed and HF as well as CF_4 and C_2F_6 are found as main gaseous reaction products. The deposited plasma polymer films on the powered electrode are strongly cross-linked due to ion bombardment. The stable plasma polymerized films from EDA are characterized by high content of nitrogen with N/C ratio of about 0.35. The plasma polymerized fluorocarbon film exhibit a reduced F/C ratio of about 1.2. Adhesion tests with human osteoblast cell line MG-63 on coated Ti6Al4V samples (polished) compared with uncoated reference sample yielded both, the enhanced cell adhesion for plasma polymerized EDA and significantly reduced cell adhesion for fluorocarbon coating, respectively. Aging of the plasma polymerized EDA film, in particular due to the reactions with oxygen from air, showed no significant change in the cell adhesion. The fluorocarbon coating with low cell adhesion is of interest for temporary implants.

*Funded by the Campus PlasmaMed.

GT1 159 A thermocouple-based remote temperature controller of an electrically floated sample to study plasma CVD growth of carbon nanotube TAKUYA MIURA, WEI XIE, TAKASHI YANASE, TARO NAGAHAMA, TOSHIHIRO SHIMADA, *Faculty of Engineering, Hokkaido University* Plasma chemical vapor deposition (CVD) is now gathering attention from a novel viewpoint, because it is easy to combine plasma processes and electrochemistry by applying a bias voltage to the sample. In order to explore electrochemistry during the plasma CVD, the temperature of the sample must be controlled precisely. In traditional equipment, the sample temperature is measured by a radiation thermometer. Since emissivity of the sample surface changes in the course of the CVD growth, it is difficult to measure the exact temperature using the radiation thermometer. In this work, we developed new equipment to control the temperature of electrically floated samples by thermocouple with Wi-Fi transmission. The growth of the CNT was investigated using our plasma CVD equipment. We examined the temperature accuracy and stability controlled by the thermocouple with monitoring the radiation thermometer. We noticed that the thermocouple readings were stable, whereas the readings of the radiation thermometer changes significantly (20 °C) during plasma CVD. This result clearly shows that the sample temperature should be measured with direct connection. On the result of CVD experiment, different structures of carbon including CNT were obtained by changing the bias voltages.

GT1 160 Non-contact temperature measurement of silicon substrate in sputtering plasma using optical interferometer TAKAYUKI OHTA, KATSUHIRO HATTORI, *Meijo University* AKINORI ODA, *Chiba Institute of Technology* HIROYUKI KOUSAKA, *Nagoya University* The substrate temperature is one of important parameters to control the plasma processing and involve the film properties or the chemistry of gas phase. High power impulse magnetron sputtering (HIPIMS) realizes a very significant fraction of the ionized species and which induced onto the substrate and heated it. It is essential to analyze the substrate temperature and the heating mechanisms. In this study, we have measured the silicon substrate temperature in HiPIMS by using the optical low-coherence interferometry. The reflected light from the front surface interferes that from back surface. The optical path length of Si wafer is obtained by the inverse Fourier transform of spectral interferogram and varies with the change in the silicon temperature. The silicon temperatures with various resistivities were measured and the change in the optical thickness increased with decreasing the resistivity owing to the carrier density of the silicon substrate. The time variation of Si substrate temperatures at various applied voltages in the HiPIMS using the titanium target was measured and the silicon temperatures increased with increasing the applied voltage.

GT1 161 Monitoring and Analyses of Initial Stages of Graphene Growth in Plasma-Enhanced Chemical Vapor Deposition YASUAKI HAYASHI, JUNYA YAMADA, MASAHIRO KAWANO, KAZUYA SANO, *Kyoto Institute of Technology* RF magnetron plasma was used for the growth of graphene. Copper films deposited by sputtering on mirror-polished silicon were used for substrates. Slant view-ports are welded to the side wall of vacuum chamber. In-situ ellipsometry is able to be carried out for the monitoring of substrate surface. The growth of graphene was started by the introduction of C_2H_4 gas in addition to hydrogen. Substrate temperature was controlled at 680°C at the first stage. An RF power up to 100 W was applied. C_2H_4 and H_2 gases were introduced with the flow rate of 20 and 10 sccm, respectively. The pressure in the vacuum chamber was maintained at 200 Pa. The result of Raman analysis showed that the ratio of height of D (1350 cm^{-1}) peak to G (1580 cm^{-1}) peak, as well as that of 2D (2700 cm^{-1}) peak to G peak, increased with time. Time evolution of height and width of graphene or graphite tips showed that, during the first 5 min, the width abruptly increases, while the increase speed of the height is lower than that after 5 min. The result implies that graphene sheets horizontally grow on the surface of substrate first before perpendicularly aligned CNWs grow. In order to analyze the first stage of the graphene growth, *in-situ* and precise measurement is required. For this purpose, *in-situ* ellipsometry should play an important role. Therefore we carried out a preliminary experiment of *in-situ* ellipsometry monitoring. Evolutions of ellipsometric parameters, Ψ and Δ, were precisely measured before the growth of graphene of 1 nm in thickness.

GT1 162 Correlation between energy of depositing particles and mobility of ITO films in the Reactive Plasma Deposition with dc arc discharge HISASHI KITAMI, KAZUYA TAKI, TOSHIYUKI SAKEMI, YASUSHI AOKI, TAKANORI KATO, *Sumitomo Heavy Industries, ltd.* A correlation between the energy of depositing particle and the mobility of ITO film has been investigated in order to elucidate the optimal energy required to form high-quality ITO film. ITO films were deposited with controlling the energy of depositing particles and according to it the condition of oxygen atmosphere was changed to get a constant carrier density of the deposited ITO films. The mobility of ITO film deposited at the substrate temperature of 200°C was found dependent on the energy of depositing particles and we concluded that the optimal energy is greater than 13 eV for ITO film deposition.

GT1 163 Glutamate biosensor based on carbon nanowalls grown using plasma enhanced chemical vapor deposition MASAKAZU TOMATSU, MINEO HIRAMATSU, *Meijo University* HIROKI KONDO, MASARU HORI, *Nagoya University* Carbon nanowalls (CNWs) are composed of few-layer graphene standing almost vertically on the substrate. Due to the large surface area of vertical nanographene network, CNWs draw attention as platform for electrochemical sensing, biosensing and energy conversion applications. In this work, CNWs were grown on nickel substrate using inductively coupled plasma with methane/Ar mixture. After the CNW growth, the surface of CNWs was oxidized using Ar atmospheric pressure plasma to obtain super-hydrophilic surface. For the biosensing application, the surface of CNWs was decorated with platinum (Pt) nanoparticles by the reduction of hydrogen hexachloroplatinate (IV) solution. The resultant Pt particle size was estimated to be 3-4 nm. From the XPS analysis, pure Pt existed without being oxidized on the CNW surface. Electrochemical surface area of the Pt catalyst was evaluated by cyclic voltammetry. Pt-decorated CNWs will be used as an electrode for electrochemical glutamate biosensing. L-glutamate is one of the most important in the mammalian central nervous system, playing a vital role in many physiological processes. Nanoplatform based on vertical nanographene offers great promise for providing a new class of nanostructured electrodes for electrochemical sensing.

GT1 164 In situ Plasma Exposure for Improved Interfaces in Atomic Layer Deposited Dielectrics on GaSb LAURA RUPPALT, ERIN CLEVELAND, JAMES CHAMPLAIN, BRAD BOOS, SHARKA PROKES, BRIAN BENNETT, *Naval Research Laboratory* Among compound semiconductors, GaSb possesses one of the highest hole mobilities, making it a promising candidate for p-channel devices for III-V-based MOS technologies. However, the requirement of a low-defect interface between the GaSb device layer and gate dielectric represents a formidable hurdle to full MOS implementation. Native oxidation of the GaSb surface typically results in a highly defective interface, trapping charge and preventing free Fermi level movement. Wet chemical approaches to removing the native oxide often lead to mixed, irreproducible results and fail to prevent rapid reoxidation upon atmospheric exposure. As an alternative to wet chemical treatments, we have investigated the use of in-situ H_2/Ar plasma for improving the interface between GaSb and atomic layer deposited (ALD) dielectrics. We have found that by exposing the native-oxide-covered GaSb to mild H_2/Ar plasma immediately prior to ALD of high-k dielectrics, one can decrease the density of interface states by two orders of magnitude, unpinning the Fermi level and enabling carrier modulation. The effectiveness of the treatment can be tuned by varying the RF plasma power, the plasma exposure time, or the substrate temperature during exposure, with higher powers, longer exposures, and higher temperatures (up to 300C) resulting in improved electrical interfaces.

GT1 165 Plasma-Modified Atomic Layer Deposition THOMAS LARRABEE,* SHARKA PROKES, *Naval Research Laboratory* PEALD is known to grow thin films with differing properties from those grown purely via chemical reactions, or thermal ALD processes. However, material properties are still limited when compared to films grown by other deposition techniques. We have used non-growth plasma steps in each ALD cycle to modify properties, in a technique we refer to as plasma-modified ALD. To study how non-growth plasma steps modify properties, we have grown metal oxides with various plasma processing steps from CCPs of Ar, O_2, N_2, and H_2 gases at relatively high pressures of 1-2 mbar. A grid is used to screen ion bombardment of the samples within a commercial Beneq TFS-200 reactor, making this plasma configuration indirect, but not remote. Several properties show significant differences between the films grown with and without these additional steps. These altered properties include crystalline orientation as indicated by XRD, plasmon resonances, photoluminescence, electron paramagnetic resonance, optical dispersion, mobilities, carrier concentrations, and resistivities. Selected plasma-initiated modifications to ALD-grown oxides of zinc, vanadium, and hafnium, and their anticipated applications in novel materials systems will be presented.

*NRC Postdoc at the Naval Research Laboratory.

GT1 166 A Study of Current and Voltage Relationships in a PECVD Process Plasma DOUGLAS KEIL, EDWARD AUGUSTYNIAK, YUKINORI SAKIYAMA, *Lam Research Corporation* LAM RESEARCH PECVD TEAM Commercial PECVD reactors present several challenges to problem of plasma diagnosis. Among them is the scarcity of available plasma metrology which can provide genuine insight and still satisfy commercial constraints. The VI probe is one of the few instruments that can meet both of these needs. This work presents a study of voltage, current, impedance, phase and harmonic trends acquired by off-the-shelf VI probes. Voltage vs Current plots in 1 to 2 Torr CCP plasmas at moderate (<3 kW) RF power levels are discussed for process relevant gasses. Non-linear features in these plots have been observed and their possible relation to Alpha-Gamma mode transitions, on-set of plasma instabilities and on wafer process results are discussed. Following S.J. You, *et al.* the use of these data to identify the primary RF power absorption mechanism is discussed. Additionally, study of harmonics can be related to plasma asymmetry, the onset of parasitic plasma and system faults. Results from both pulsed and continuous plasmas are also discussed.

[1]S. J. You *et al.*, J. Appl. Phys. **94** (2003).

GT1 167 Surface Passivation of ZrO2 Artificial Dentures by Magnetized Coaxial Plasma deposition SOYA ARAI, *Graduate School of Science and Technology, Nihon University* SATOSHI KURUMI, KEN-ICHI MATSUDA, KAORU SUZUKI, *College of Science and Technology, Nihon University* KATSUYA HARA, TATSUYA KATO, *Graduate School of Science and Technology, Nihon University* TOMOHIKO ASAI, *College of Science and Technology, Nihon University* HIDEHARU HIROSE, SHIGEYUKI MASUTANI, *Nihon University School of Dentistry* NIHON UNIVERSITY TEAM Recent growth and fabrication technologies for functional materials have been greatly contributed to drastic development of oral surgery field. Zirconia based ceramics is expected to utilize artificial dentures because these ceramics have good biocompatibility, high hardness and aesthetic attractively. However, to apply these ceramics to artificial dentures, this denture is removed from a dental plate because of weakly bond. For improving this problem, synthesis an Al passivation-layer on the ceramics for bonding with these dental items is suitable. In order to deposit the passivation layer, we focused on a magnetized coaxial plasma deposition (MCPD). The greatest characteristic of MCPD is that high-melting point metal can be deposited on various substrates. Additionally, adhesion force between substrate and films deposited by the MCPD is superior to it of general deposition methods. In this study, we have reported on the growth techniques of Al films on ZrO2 for contributing to oral surgery by the MCPD. Surface of deposited films shows there were some droplets and thickness of it is about 200 nm. Thickness is increased to 500 nm with increasing applied voltage.

GT1 168 Current-Voltage Characteristics and Deposition of AlTiN Thin Films by High Power Impulse Magnetron Sputtering Process WAN-YU WU, *Da-Yeh University, Taiwan* AMEI SU, YAWEI LIU, *Fujian University of Technology, China* CHI-MING YEH, WEI-CHIH CHEN, CHI-LUNG CHANG, *MingDao University, Taiwan* In this study, AlTiN thin films were deposited using a high power impulse magnetron sputtering (HiPIMS) process under a unipolar mode. The AlTi target had a composition of 70 at% Al and 30 at% Ti. Nitrogen was used as the reactive gas to deposite AlTiN thin films along with Ar gas at a working pressure of 1×10^{-3} torr. The target voltage and current were measured at different conditions including various duty cycles from 1 to 5%, pulse durations from 50 to 400 μs, target powers from 0.6 to 1.8 kW, and N2/Ar ratios from 0 to 1. Depending on the deposition condition, peak powers in the range of 104 to 105 W were observed. The effect of deposition conditions were discussed. For film deposition, the pulse duration and the duty cycle were fixed at 100 μs and 3%, respectively. A fixed bias of -150 V was applied to the substrates, including Si wafer, 304 stainless steel, and tungsten carbide.It was found that the nitrogen content increases with the N2/Ar ratio and then saturates. With increasing target power, a higher N2/Ar ratio was required for the AlTiN thin films to have a better mechanical properties. Meanwhile, the hardness of the AlTiN thin films also increases with the target power. The highest hardness of 41 GPa was observed as the N2/Ar ratio was 0.9 and the power was 1.8 kW. It was found that the amount Al-N bonding and the distribution of AlN phase within the AlTiN thin films play an important role in determining the mechanical properties.

GT1 169 PLASMA PROPULSION AND AERODYNAMICS

GT1 170 Study of plasma induced flow forming mechanism using the Schlieren method NAOHIKO SHIMURA, MOTOFUMI TANAKA, KIYOYUKI AMEMORI, HIROYUKI YASUI, *Toshiba Corporation* As one of the active flow control device, a non-thermal dielectric barrier discharge plasma actuator is well known and paid attention. However, the effect of applied voltage waveform to the spatial distribution of the electric discharge and induced flow is not understood. We visualized spacio-temporal evolution of an air density due to the induced flow by Schlieren imaging method with high speed camera, and discuss the relationship between the time variation of applied voltage dV/dt and induced flow. Sinusoidal and triangular waveform voltages were applied to the plasma actuator. It was observed that induced flow was formed with phase of dV/dt<0 of sinusoidal voltage waveform. In the case of triangular voltage waveform, it found that the induced flow is faster with increasing the time of dV/dt<0 in one cycle. These phenomena can be considered as follows. In the phase dV/dt>0, the streamer easily progresses to the dielectric surface, and the dielectric surface is charged up immediately and electric field is weakened by the surface charge, and then induced flow is not formed. On the other hand, in the case of dV/dt<0, because streamer is difficult to progress, the electric field to accelerate the positive ions is not cancelled with surface charge.

GT1 171 Simulation of inductive flow controlled by using Microplasma Actuator KAZUO SHIMIZU, *Organization for Innovation and Social Collaboration, Shizuoka University* AKIHIKO ITO, *Graduate school of engineering, Shizuoka University* MARIUS BLAJAN, *Organization for Innovation and Social Collaboration, Shizuoka University* HITOKI YONEDA, *Institute for Laser Science, The University of Electro-Communications* Plasma actuator is a novel device for flow control because it has many advantages such as simple construction, no moving part, and quick response. In this study, microplasma actuator with four independent channels was used to generate upward and downward flow. The discharge gap was set at 25 μm, enabling the discharge to occur at the voltage of about 1 kV. Due to low discharge voltage the applied high-voltage could be controlled using FET switches easily. This enables to generate flexible flow. When a AC voltage of 1.4 kV and 20 kHz was applied, 0.6 m/s upward flow and 0.2 m/s downward flow were obtained. The numerical simulation using Suzen model was also carried out to investigate the flow velocity near the electrode surface since flow observation was difficult due to the reflected light from electrodes in PTV. In the simulation, we confirmed that the intensity of upward and downward flow was close to that in experiments. After applying a AC voltage for 2.5 ms, flow control was not finished, and considered to be the transient state. Vortices with the height of about 1.5 mm were occurred in both cases of experiments and the numerical simulations. On the other hand, after driving for 60 ms, the vortex development stopped and this stage was considered to be the steady state.

GT1 172 Experimental results of an iodine plasma in PEGASES gridded thruster* PASCALINE GRONDEIN, ANE AANESLAND, *Laboratoire de Physique des Plasmas - CNRS - UMPC* In the electric gridded thruster PEGASES, both positive and negative ions are expelled after extraction from an ion-ion plasma. This ion-ion plasma is formed downstream a localized magnetic field placed a few centimeters from the ionization region, trapping and cooling down the electron to allow a better attachment to an electronegative gas. For this thruster concept, iodine has emerged as the most attractive option. Heavy, under diatomic form and therefore good for high thrust, its low ionization threshold and high electronegativity lead to high ion-ion densities and low RF power. After the proof-of-concept of PEGASES using SF6 as propellant, we present here experimental results of an iodine plasma studied inside PEGASES thruster. At solid state at standard temperature and pressure, iodine is heated to sublimate, then injected inside the chamber where the neutral gas is heated and ionized. The whole injection system is heated to avoid deposition on surfaces and a mass flow controller allows a fine control on the neutral gas mass flow. A 3D translation stage inside the vacuum chamber allows volumetric plasma studies using electrostatic probes. The results are also compared with the global model dedicated to iodine as propellant for electric gridded thrusters.

*This work has been done within the LABEX Plas@par project, and received financial state aid managed by the Agence Nationale de la Recherche, as part of the programme "Investissements d'avenir."

GT1 173 Electron Extraction Mechanisms of a Micro ECR Neutralizer* YOSHINORI TAKAO, KENTA HIRAMOTO, *Yokohama National University* YUICHI NAKAGAWA, YUSUKE KASAGI, HIROYUKI KOIZUMI, KIMIYA KOMURASAKI, *The University of Tokyo* A neutralizer is one of the indispensable components for ion propulsion systems. To design a better performance neutralizer the mechanisms of electron extraction from its plasma source through orifices should be elucidated. In the present study, three-dimensional particle simulations have been carried out for a 4.2-GHz microwave discharge neutralizer, where the size of the discharge chamber is 20 × 20 × 4 mm^3 and a xenon electron cyclotron resonance plasma is employed. The numerical model is composed of a particle-in-cell simulation with a Monte Carlo collision algorithm for the kinetics of charged particles, a finite-difference time-domain method for the electromagnetic fields of microwaves, and a finite element analysis for the magnetostatic fields of permanent magnets. The calculations were conducted at the gas pressure of 1 mTorr and the absorbed power of 0.3 W. The simulation results have indicated that the electrostatic field of the plasma has a dominant influence on the electron extraction, where electrons are not extracted unless the effect of the electrostatic field is taken into account in the calculations.

*This work was supported in part by JSPS KAKENHI Grant No. 25289304. Part of the simulations was performed on the KDK computer system at RISH, Kyoto University.

GT1 174 Measurement of erosion in helicon plasma thrusters using the VASIMR® VX-CR device JUAN IGNACIO DEL VALLE GAMBOA, JOSE CASTRO-NIETO, JARED SQUIRE, MARK CARTER, FRANKLIN CHANG-DIAZ, *Ad Astra Rocket Company* The helicon plasma source is one of the principal stages of the high-power VASIMR® electric propulsion system. The VASIMR® VX-CR experiment focuses solely on this stage, exploring the erosion and long-term operation effects of the VASIMR helicon source. We report on the design and operational parameters of the VX-CR experiment, and the development of modeling tools and characterization techniques allowing the study of erosion phenomena in helicon plasma sources in general, and stand-alone helicon plasma thrusters (HPTs) in particular. A thorough understanding of the erosion phenomena within HPTs will enable better predictions of their behavior as well as more accurate estimations of their expected lifetime. We present a simplified model of the plasma-wall interactions within HPTs based on current models of the plasma density distributions in helicon discharges. Results from this modeling tool are used to predict the erosion within the plasma-facing components of the VX-CR device. Experimental techniques to measure actual erosion, including the use of coordinate-measuring machines and microscopy, will be discussed.

GT1 175 Trajectory Control of Small Rotating Projectiles by Laser Sparks ANDREY STARIKOVSKIY, CHRISTOPHER LIMBACH, RICHARD MILES, *Princeton University* The possibility of controlling the trajectory of the supersonic motion of a rotating axisymmetric projectile using a remotely generated laser spark was investigated. The dynamic images of the interaction of thermal inhomogeneity created by the laser spark with the bow shock in front of the projectile were obtained. The criterion for a strong shock wave interaction with the thermal inhomogeneity at different angles of a shock wave was derived. Significant changes in the configuration of the bow shock wave and changes in the pressure distribution over the surface of the rotating projectile can appear for laser spark temperature of $T' = 2500$-3000 K. The experiment showed that strong interaction takes place for both plane and oblique shock waves. The measurement of the velocity of the precession of the rotating projectile axis from the initial position in time showed that the angle of attack of the projectile deviates with a typical time of perturbation propagation along the projectile's surface. Thus the laser spark can change the trajectory of the rotating projectile, moving at supersonic speed, through the creation of thermal heterogeneity in front of it.

GT1 176 Plasma Assisted Combustion Mechanism for Hydrogen and Small Hydrocarbons ANDREY STARIKOVSKIY, *Princeton University* NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* The main mechanisms of nonequilibrium gas excitation and their influence on the ignition and combustion were briefly discussed. Rotational excitation, vibrational excitation, electronic excitation, dissociation by electron impact and ionization were all analyzed, as well as the ways in which the selectivity of the gas excitation in the discharge can be controlled. The model consists of two parts. The first part describes gas excitation by electron impact – rotational, vibrational and electronic states population by pulsed discharges. The second part considers energy relaxation in the plasma (formation of Maxwell-Boltzmann equilibrium across translational, vibrational and electronic degrees of freedom of molecules), quenching and decomposition of excited states, their reactions and recombination – with formation of thermally-equilibrium pool of radicals, which could be considered as initial conditions for any detailed combustion kinetic mechanism. The mechanism was verified against available kinetic data in a wide temperature range. Despite of some lack of knowledge of mechanism details, nonequilibrium plasma demonstrates great potential for controlling ultra-lean, ultra-fast, low-temperature flames and is an extremely promising technology for a very wide range of applications.

GT1 177 Non-equilibrium Numerical Analysis of Microwave-supported Detonation Threshold Propagating through Diatomic Gas HIROYUKI SHIRAISHI, *Daido University* Microwave-supported Detonation (MSD), one type of Microwave-supported Plasma (MSP), is considered as one of the most important phenomena because it can generate high pressure and high temperature for beam-powered space propulsion systems. In this study, I numerically simulate MSD waves propagating through a diatomic gas. In order to evaluate the threshold of beam intensity, I use the physical-fluid dynamics scheme, which has been developed for simulating unsteady and non-equilibrium LSD waves propagating through a hydrogen gas.

GT1 178 Ion and neutral dynamics in Hall plasma accelerator ionization instabilities* ANDREA LUCCA FABRIS, CHRISTOPHER YOUNG, MARK CAPPELLI, *Stanford Plasma Physics Laboratory* Hall thrusters, the extensively studied $E \times B$ devices used for space propulsion applications, are rife with instabilities and fluctuations. Many are thought to be fundamentally linked to microscopic processes like electron transport across magnetic field lines and propellant ionization that in turn affect macroscopic properties like device performance and lifetime. One of the strongest oscillatory regimes is the "breathing mode," characterized by a propagating ionization front, time-varying ion acceleration profiles, and quasi-periodic 10-50 kHz current oscillations. Determining the temporal and spatial evolution of plasma properties is critical to achieving a fundamental physical understanding of these processes. We present non-intrusive laser-induced fluorescence measurements of the local ion and neutral velocity distribution functions synchronized with the breathing mode oscillations. Measurements reveal strong ion velocity fluctuations, multiple ion populations arising in narrow time windows throughout the near-field plume, and the periodic population and depopulation of neutral excited states. Analyzing these detailed experimental results in the context of the existing literature clarifies the fundamental physical processes underlying the breathing mode.

*This work is sponsored by the U.S. Air Force Office of Scientific Research with Dr. M. Birkan as program manager. C.Y. acknowledges support from the DOE NSSA Stewardship Science Graduate Fellowship under contract DE-FC52-08NA28752.

SESSION HT1: ATOMIC AND MOLECULAR SCATTERING DATA FOR PLASMA AND RELATED APPLICATIONS WORKSHOP I

Tuesday Evening, 13 October 2015; Room: 301 B at 20:00; Alisher Kadyrov, Curtin University, presiding

Invited Papers

20:00

HT1 1 Application of the Convergent Close-Coupling method to collisions of electrons, positrons, and protons with light atomic and molecular targets

IGOR BRAY,* *Curtin University of Technology*

The Convergent Close-Coupling (CCC) method for electron-atom collisions has been applied successfully for around two decades for quasi one- and two-electron atomic targets. The underlying engine is the complete Laguerre basis for treating to convergence the target discrete and continuous spectra via a square-integrable approach, together with a formulation of the close-coupling equations in momentum space. The method has continued to be extended, and now incorporates collisions with positrons with allowance for positronium formation. This is a major advancement because it addresses the complexity associated with treating multi-center collision problems. These techniques have then been readily transferred to collisions with protons, where charge-exchange can be a substantial scattering outcome. The latter also required a move to solving the CCC equations using an impact parameter formalism. Most recently, in addition to the extension of the variety of projectiles, the collision targets have been generalized to molecules. Presently, just the H_2^+ and the H_2 molecules have been implemented. In the talk a broad range of applications of the CCC method will be discussed and future developments will be indicated.

*coauthors: A. S. Kadyrov, D.V. Fursa, I. Abdurakhmanov, M. Zammit.

20:30

HT1 2 Benchmark calculations for electron collisions with complex atoms: accuracy, convergence and completeness*
OLEG ZATSARINNY, *Drake University*

Over the past decade, we have developed a highly flexible B-spline R-matrix (BSR) method [1] that has some advantages compared to the standard R-matrix (close-coupling) approach. The two essential refinements are i) the capability for using the flexible term-dependent one-electron orbitals, and ii) the use of B-splines as a universal and effectively complete basis to generate the R-matrix basis. These features allow us to achieve a high accuracy in the target description, as well as a truly consistent treatment of the scattering system. The BSR code was successfully applied to many problems of electron collisions from atoms and ions, with special emphasis was placed on complex, open-shell targets. Often considerable *improvement* was obtained in comparison with previous calculations. Many examples can be found in a recent Topical Review [2]. More recently, the BSR complex has been extended to i) the fully relativistic Dirac scheme and ii) intermediate energies using the continuum pseudo-state approach. These extensions allow for an accurate treatment of *heavy targets* as well as a fully non-perturbative way to handle electron-impact *ionization*, including such highly correlated processes as ionization plus simultaneous excitation. During the last years we developed parallel versions of our BSR and DBSR codes. They made it possible to carry out large-scale $R-$matrix with pseudo-states (RMPS) calculations and thereby provide *converged* (with respect to the number of coupled states) results for electron impact excitation of individual target states. For many systems our calculations revealed dramatic reductions of the predicted excitation cross-sections at intermediate energies, due to the strong influence of coupling to the target continuum. These results raise questions about the absolute normalization in several published measurements. Our RMPS calculations represent the extensive and *complete* sets of electron scattering data ready for applications.

*Research Supported by the United States National Science Foundation.

[1]O. Zatsarinny, Comput. Phys. Commun. **174**, 273 (2006).
[2]O. Zatsarinny and K. Bartschat, J. Phys. B: At. Mol. Opt. Phys. **46**, 112001 (2013).

21:00

HT1 3 The Empowerment of Plasma Modeling by Fundamental Electron Scattering Data*
MARK J. KUSHNER, *University of Michigan*

Modeling of low temperature plasmas addresses at least 3 goals – investigation of fundamental processes, analysis and optimization of current technologies, and prediction of performance of as yet unbuilt systems for new applications. The former modeling may be performed on somewhat idealized systems in simple gases, while the latter will likely address geometrically and electromagnetically intricate systems with complex gas mixtures, and now gases in contact with liquids. The variety of fundamental electron and ion scattering data (FSD) required for these activities increases from the former to the latter, while the accuracy required of that data probably decreases. In each case, the fidelity, depth and impact of the modeling depends on the availability of FSD. Modeling is, in fact, empowered by the availability and robustness of FSD. In this talk, examples of the impact of and requirements for FSD in plasma modeling will be discussed from each of these three perspectives using results from multidimensional and global models. The fundamental studies will focus on modeling of inductively coupled plasmas sustained in Ar/Cl_2 where the electron scattering from feed gases and their fragments ultimately determine gas temperatures. Examples of the optimization of current technologies will focus on modeling of remote plasma etching of Si and Si_3N_4 in $Ar/NF_3/N_2/O_2$ mixtures. Modeling of systems as yet unbuilt will address the interaction of atmospheric pressure plasmas with liquids

*Work was supported by the US Dept. of Energy (DE-SC0001939), National Science Foundation (CHE-124752), and the Semiconductor Research Corp.

21:30

HT1 4 Scaling of plane-wave Born cross sections for electron-impact excitation of neutral atoms and molecules
HIROSHI TANAKA, *Department of Physics, Sophia University*

We review the scaling of plane-wave Born cross sections for electron-impact excitation of neutral atoms and molecules. The scaling method is applied to integrated cross sections for electric dipole-allowed transitions. As introduced in the BEB scaling model for ionization cross sections, this scaling replaces the incident electron energy T in the first-order PWB cross sections by $T + B + E$, where B is the ionization energy, or the binding energy, of the target electron, and E is the excitation energy. Note in a generic form, first-order PWB cross sections are defined as $\sigma_{PWB} = (4\pi a_0^2 R/T)\ \mathrm{GOS}_{PWB}(T)$, where a_0 is the Bohr radius, R is the Rydberg energy, and GOS is the *Bethe* generalized oscillator strength. In the scaling, though two approaches, computational and experimental have been applied, the latter is presented at this meeting in which the *Bethe* GOS is replaced by the *apparent* GOS determined by the experiments. Representative examples show that an simple improvement scaled by $T + B + E$ extends the usage of the Born-Bethe approximation into the *intermediate* region, thereby bridging the gap between the two regions categorized conventionally as slow and fast collisions.

SESSION IW1: DISINFECTION/STERLIZATION BY PLASMA

Wednesday Morning, 14 October 2015; Room: 301 B at 8:00; Thomas Von Woedtke, INP Greifswald, presiding

Invited Papers

8:00

IW1 1 High sensitive virus and bacteria detection using plasma-surface-functionalized and antibody-integrated carbon nanomaterials*

MASAAKI NAGATSU, *Shizuoka University*

In this study we will present our recent results on the virus and bacteria detection system using the surface-functionalized carbon-encapsulated magnetic nanoparticles (NPs) fabricated by dc arc discharge, and carbon nanotube(CNT) dot-array prepared with a combined thermal and plasma CVD system. Surface functionalization of their surfaces has been carried out by plasma chemical modification using a low-pressure RF plasma for carbon-encapsulated magnetic NPs, and an ultrafine atmospheric pressure plasma jet(APPJ) for CNT dot-array substrate. After immobilization of the relevant biomolecules onto the surface of nano-structured materials, we have carried out the experiments on virus or bacteria detection using these surface-functionalized nano-structured materials. From the preliminary experiments with carbon-encapsulated magnetic NPs, we confirmed that influenza A (H1N1) virus concentration of 17.3-fold was achieved by using anti-influenza A virus hemagglutinin (HA) antibody. We have also confirmed a rapid and sensitive detection of *Salmonella* using the proposed method. The feasibility of CNT dot-array as a microarray biosensor has been studied by maskless functionalization of amino (-NH_2) and carboxyl (-COOH) groups onto CNTs by using a ultrafine APPJ with a micro-capillary. The experimental results of chemical derivatization with the fluorescent dye showed that the CNT dot-array was not only functionalized with amino group and carboxyl group, but was also functionalized without any interference between functional groups. The success of maskless functionalization in the line pattern provides a feasibility of a multi-functionalization CNT dot-array device for future application of a microarray biosensor.

*This work has been supported in part by Grant-in-Aid for Scientific Research (Nos. 21110010 and 25246029) from the JSPS and the International Research Collaboration and Scientific Publication Grant (DIPA-23.04.1.673453/2015) from DGHE Indonesia.

Contributed Papers

8:30

IW1 2 Innovative Plasma Disinfection Technique with the Reduced-pH Method and the Plasma-Treated Water (PTW) -Safety and Powerful Disinfection with Cryopreserved PTW- * KATSUHISA KITANO, *Eng., Osaka Univ.* SATOSHI IKAWA, YOICHI NAKASHIMA, *TRI Osaka* ATSUSHI TANI, *Sci., Osaka Univ.* TAKASHI YOKOYAMA, *Eng., Osaka Univ.* TOMOKO OHSHIMA, *Dental Medicine, Tsurumi Univ.* Among the applications of the plasma disinfection to human body, plasma sterilization in liquid is crucial. We found that the plasma-treated water (PTW) has strong bactericidal activity under low pH condition and the half-lives of its activity depend on temperature. Lower temperature brings longer half-life and the bactericidal activity of PTW can be kept by cryopreservation. These physicochemical properties were in accordance with Arrhenius equation both in liquid and solid states. From the experimental results of ESR (Electron Spin Resonance) measurement of O_2^- in liquid against PTW with spin trapping method, half-lives of PTW were also in accordance with Arrhenius equation. It suggests that high concentration PTW as integrated value can be achieved by cooling of plasma apparatus. Pure PTW has disinfection power of 22 log reduction (B. subtilis). This corresponds to 65% H2O2, 14% hypochlorous acid and 0.33% peracetic acid, which are deadly poison for human. On the other hand, PTW is deactivated soon at body temperature. This indicates that toxicity to human body seems to be low. PTW, which is a sort of indirect plasma exposure, with pH and temperature controls could be applied for safety and powerful disinfection.

*MEXT (15H03583, 23340176, 25108505). NCCE (23-A-15).

8:45

IW1 3 Disinfection of Streptococcus mutans Biofilm by a Non-Thermal Atmospheric Plasma Brush QING HONG, XIAO-QING DONG, *Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO, USA* MENG CHEN, *Nanova, Inc., Columbia, MO, USA* YUANXI XU, HONGMIN SUN, *Department of Internal Medicine, University of Missouri, Columbia, MO, USA* LIANG HONG, *Department of Pediatric and Community Dentistry, College of Dentistry, the University of Tennessee Health Science Center, Memphis, TN, USA* QINGSONG YU, *Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO 65211, USA* This study investigated the argon plasma treatment effect on disinfecting dental biofilm by using an atmospheric pressure plasma brush. S. mutans biofilms were developed for 3 days on the surfaces of hydroxyapatite discs, which were used to simulate human tooth enamel. After plasma treatment, cell viability in the S. mutans biofilms was characterized by using MTT assay and confocal laser scanning microscopy (CLSM). Compared with the untreated control group, about 90% and 95% bacterial reduction in the biofilms was observed after 1 and 5 min plasma treatment, respectively. Scanning electron microscopy examination indicated severe cell damages occurred on the top surface of the plasma treated biofilms. CLSM showed that plasma treatment was effective as deep as 20 μm into the biofilms.

When combined with 0.2% chlorhexidine digluconate solution, the plasma treatment became more effective and over 96% bacterial reduction was observed with 1 min plasma treatment. These results indicate that plasma treatment is effective and promising in dental biofilm disinfection.

9:00

IW1 4 Uniform dose atmospheric pressure microplasma exposure of individual bacterial cells* DAVID RUTHERFORD, CHARLES MAHONY, SARAH SPENCE, FATIMA PEREZ-MARTIN, COLIN KELSEY, NEIL HAMILTON, *Ulster University* DECLAN DIVER, EUAN BENNET, HUGH POTTS, *University of Glasgow* DAVIDE MARIOTTI, DAVID MCDOWELL, PAUL MAGUIRE, *Ulster University* Plasma – bacteria interactions have been studied for some time with a view to using plasma exposure for wound healing, sterilization and decontamination. While high efficacy has been demonstrated, important fundamental mechanisms are not understood and may be critical for ultimate acceptance. The dose variation across the exposed population and the impact of non-lethal exposure on subsequent bacterial growth are important issues. We demonstrate that individual bacterial cells can remain viable after exposure to a uniform plasma dose. Each bacteria cell (E coli) is delivered to the atmospheric pressure plasma in an aerosolised droplet (d $\sim$ 10 micron). The estimated plasma density is 1E13 – 1E14 cm^{-3}, gas temperature <400 K, and exposure times vary between 0.04 and 0.1ms [1]. Droplet evaporation in flight is $\sim$ 2 micron and plasma – cell interactions are mediated by the surrounding liquid (Ringers solution) where plasma-induced droplet surface chemistry and charging is known to occur. We report the cell viability and recovery dynamics of individual exposed cells as well as impact on DNA and membrane components with reference to measured plasma parameters.

*This research was funded by EPSRC (Grants: EP/K006088/1 & EP/K006142/1).

[1]P. Maguire *et al*, Appl. Phys. Lett. **106**, 224101 (2015).

9:15

IW1 5 Soluble Proteins Form Film by the Treatment of Low Temperature Plasma* SANAE IKEHARA, *Natl. Inst. of Adv. Ind. Sci. and Tech. (AIST)* HAJIME SAKAKITA, *Electronics and Phot. Res. Inst., AIST* KENJI ISHIKAWA, *Graduate School of Engineering, Nagoya Univ.* YOSHIHIRO AKIMOTO, *Dept.of Anat. Kyorin Univ. school of med* HAYAO NAKANISHI, *Aichi Cancer Cent. Hosp.* NOBUYUKI SHIMIZU, *SANNO Hosp.* MASARU HORI, *Graduate School of Engineering, Nagoya Univ.* YUZURU IKEHARA, *Biotech. Res. Inst.for Drug Disc., AIST* It has been pointed out that low temperature plasma in atmosphere was feasible to use for hemostasis without heat injury. Indeed, earlier studies demonstrated that low temperature plasma played an important role to stimulate platelets to aggregate and turned on the proteolytic activities of coagulation factors, resulting in the acceleration of the natural blood coagulation process. On the other hands, our developed equips could immediately form clots upon the contact with plasma flair, while the histological appearance was different from natural coagulation. Based on these findings in formed clots, we sought to determine if plasma flair supplied by our devices was capable of forming film using a series of soluble proteins Following plasma treatment, films were formed from bovine serum albumin, and the other plasma proteins at physiological concentration. Analysis of trans-electron microscope demonstrated that plasma treatment generated small protein particles and made them fuse to be larger aggregations The combined results demonstrated that plasma are capable of aggregating soluble proteins and that platelets and coagulation factors are not necessary for plasma induced blood coagulation.

*Supported in part by Grants-in-Aid for Scientific Research on Priority Area (21590454, 24590498, and 24108006 to Y. I.).

SESSION IW2: ION ASSISTED DEPOSITION

Wednesday Morning, 14 October 2015
Room: 308 AB at 8:00
Mineo Hiramatsu, Meijo University, presiding

Contributed Papers

8:00

IW2 1 Superhard Coatings Synthesis Assisted by Pulsed Beams of High-Energy Gas Molecules* ALEXANDER METEL, VASILY BOLBUKOV, MARINA VOLOSOVA, SERGEI GRIGORIEV, YURY MELNIK, *Moscow State University of Technology "STANKIN"* DEPARTMENT OF HIGH-EFFICIENCY MACHINING TECHNOLOGIES TEAM For production of nanocomposite superhard (HV 5000) and fracture-tough coatings on dielectric substrates a source of metal atoms accompanied by pulsed beams of 30-keV neutral molecules was used. The source is equipped with two parallel equipotential grids placed between a magnetron target and a substrate. Negative high-voltage pulses applied to the high-transparency grids accelerate from the magnetron plasma ions, which are transformed into high-energy neutral molecules due to charge-exchange collisions with gas molecules between the grids. Mixing of the substrate and coating materials through bombardment by high-energy gas molecules results in an adequate compressive stress of the coating and interface width exceeding 1 μm, which allows deposition of 100-μm-thick coatings with a perfect adhesion.

*The work was supported by the Grant No. 14-29-00297 of the Russian Science Foundation.

8:15

IW2 2 Effects of ion bombardments on electronic properties of amorphous carbon films grown by plasma-enhanced chemical vapor deposition HIROTSUGU SUGIURA, LINGYUN JIA, HIROKI KONDO, KENJI ISHIKAWA, KEIGO TAKEDA, MAKOTO SEKINE, MASARU HORI, *Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan* Amorphous carbon (a-C) films show huge variety of optical and electronic properties, because of a mixture of sp^2 and sp^3 bonding carbon. Therefore, it's expected to apply a-C films to optical and electrical device applications, such as solar cells. However, there has been no report about a photovoltaic effect in a-C junction solar cells. Growth mechanism and relationship between plasma factors and film properties are not clarified yet. It is important to clear the effect of radicals and ions on their film properties. In this study, a-C films were synthesized by a radical-injection plasma-enhanced chemical vapor deposition at 550 degree C, in which 20 or 250 W VHF powers was applied to capacitively-coupled plasma (CCP). And, RF bias powers were applied to substrates to control the self-bias voltage (V_{DC}). V_{DC} values were adjusted to 200, 275, and 400V, respectively. As the CCP power increased, optical emission intensity of C_2 radicals increased, and G-band peaks became shaper which indicates development of graphitization. With increasing the V_{DC}, optical band gap decreased and conductivity increased. From these results, it was found that formation of sp^2 bonds and modification of energy bandgap can be realized by control of ion energy.

8:30

IW2 3 In-situ monitoring of plasma ion assisted deposition (PIAD) processes* JENS HARHAUSEN, RÜDIGER FOEST, DETLEF LOFFHAGEN, *Leibniz Institute for Plasma Science and*

Technology, Felix-Hausdorff-Straße 2, 17489 Greifswald, Germany Present photonics applications depend on accurate production techniques. Plasma based processes might be termed the backbone of multilayer optical coatings which are the key components of dielectric mirrors, filters or antireflectives. However, the sector strongly relies on process recipies based on empirical optimization of thin film properties. Limitations in quality, repeatability and yield are faced. In this contribution results of efforts on plasma characterization of a beam source employed for PIAD are presented. Data on electron and ion kinetics as well as optical emission facilitated a comprehensive understanding of underlying physics of ion beam generation and propagation in an industrial type batch coater. In order to promote the development of next generation production plants, concepts for in-situ diagnostics are investigated. Results from monitoring of optical radiance of the plasma plume near the source and electron density near the substrates are discussed. The novel concept of the multipole resonance probe is applied during deposition in order to trace variations not only in magnitude of plasma density, but also its spatial distribution. Coating materials comprise TiO_2, Ta_2O5, Al_2O_3 and SiO_2.

*Funded by the German Federal Ministry of Education and Research (BMBF) under Grant 13N13213).

8:45

IW2 4 ICP-Enhanced Sputter Deposition for Reactivity Control and Low-Temperature Formation of a-IGZO Films* YUICHI SETSUHARA, KEITARO NAKATA, YOSHIKATSU SATAKE, KOSUKE TAKENAKA, GIICHIRO UCHIDA, *Osaka University* AKINORI EBE, *EMD Corporation* Inductively coupled plasma (ICP) - enhanced sputter deposition for a-IGZO channel TFTs fabrication have been performed. This advantage of fine control of reactivity during the deposition process is of great significance for film deposition of the transparent amorphous oxide semiconductor, a-$InGaZnO_x$ (a-IGZO), whose electrical properties are significantly sensitive to the reactivity during the film deposition. The a-IGZO film deposition with addition of H_2 gas were performed in order to control oxidation process during a-IGZO film formation via balance between oxidation-reduction. The results of optical emission spectrum indicate the possibility for the suppression of oxidation by oxygen atoms of a-IGZO films during deposition due to addition of H_2 gas. The characteristics of TFT fabricated with IGZO film via plasma-enhanced magnetron sputter deposition system have been investigated. The result exhibits that the possibility of expanding process window for control of balance between oxidization and reduction by addition of H_2 gas. The a-IGZO channel TFTs fabricated plasma-enhanced reactive sputtering system with addition of H_2 gas exhibited good performance of field-effect mobility 15.3 cm^2 $(Vs)^{-1}$ and subthreshold gate voltage swing (S) of 0.48 V $decade^{-1}$.

*This work was partly supported by ASTEP (JST) and Grant-in-Aid for Challenging Exploratory Research (JSPS).

9:00

IW2 5 Plasma deposition of amorphous silicon carbide thin films irradiated with neutrons J. HURAN, P. BOHACEK, M. KUCERA, *IEE SAS, Bratislava, Slovakia* A. KLEINOVA, *Polymer Institute, SAS, Bratislava, Slovakia* V. SASINKOVA, *Institute of Chemistry, SAS, Bratislava, Slovakia* IEE SAS, BRATISLAVA, SLOVAKIA TEAM, POLYMER INSTITUTE, SAS, BRATISLAVA, SLOVAKIA TEAM, INSTITUTE OF CHEMISTRY, SAS, BRATISLAVA, SLOVAKIA TEAM Amorphous silicon carbide and N-doped silicon carbide thin films were deposited on P-type Si(100) wafer by plasma enhanced chemical vapor deposition (PECVD) technology using silane, methane, ammonium and argon gases. The concentration of elements in the films was determined by RBS and ERDA method. Chemical compositions were analyzed by FTIR spectroscopy. Photoluminescence properties were studied by photoluminescence spectroscopy (PL). Irradiation of samples with various neutron fluencies was performed at room temperature. The films contain silicon, carbon, hydrogen, nitrogen and small amount of oxygen. From the IR spectra, the films contained Si-C, Si-H, C-H, Si-N, N-H and Si-O bonds. No significance effect on the IR spectra after neutron irradiation was observed. PL spectroscopy results of films showed decreasing PL intensity after neutron irradiation and PL intensity decreased with increased neutron fluencies. The measured current of the prepared structures increased after irradiation with neutrons and rise up with neutron fluencies.

9:15

IW2 6 Feature Scale Simulations of Deposition Processes PAUL MOROZ, *Tokyo Electron U.S. Holdings, Inc.* DANIEL J. MOROZ, *University of Pennsylvania* Deposition processes, together with etching, planarization, and implantation, represent the basis of materials processing. Requirements for the accuracy of processing are becoming ever more stringent and thus the role of numerical simulations grows. The feature scale simulator FPS3D [1,2] allows detailed simulation of simultaneous deposition, etching, and implantation processes. In this report, we emphasize FPD3D's capability to simulate deposition. We simulate and analyze the deposition of copper seed layer films into high-aspect-ratio features, examining the profile conformity and feature-filling quality of the deposited copper layers and their dependence on the energy and angular distributions of incoming fluxes of species. A number of cases were analyzed, including the following: isotropic flow of Cu, directional flow of Cu, isotropic flow of Cu together with ions, and directional flow of Cu together with ions. It was found that directional flow of Cu together with ions has significant advantages over other options, allowing efficient Cu seed layer deposition even for small high-aspect-ratio features. We also discuss detailed structure of deposited layers such as agglomeration into islands with specific orientation and film roughness.

[1]P. Moroz, IEEE Trans. on Plasma Science **39**, 2804 (2011).
[2]P. Moroz, D. J. Moroz, ECS Transactions **50**, 61 (2013).

SESSION IW3: MODELING AND SIMULATION I

Wednesday Morning, 14 October 2015; Room: 305 AB at 8:00; Ute Ebert, Eindhoven University of Technology, presiding

Invited Papers

8:00

IW3 1 Numerical Uncertainty Estimation for Stochastic Particle-in-Cell Simulations Applied to Verification and Validation*

KEITH CARTWRIGHT, *Sandia National Laboratories*

Numerical error estimation is a key component in verification, validation, and uncertainty quantification. For ParticleIn-Cell (PIC) plasma simulations, error estimation is complicated due to the presence of stochastic noise and multiple convergence parameters (grid size, time step, macro particle weight). In this talk, we will discuss recent developments for the Stochastic Richardson Extrapolation Based Error Quantification method (StREEQ). This method at its core is a multi-regression technique, where nine regression models and multiple bootstrap samples propagate uncertainties due to the fit and the stochasticity of the underlying data for an appropriate error model with unknown convergence rates. Recently, automation of the convergence parameter domain selection has been implemented; this enables efficient error estimation for large data sets, including analysis of multiple quantities of interest and time dependent data. This method is demonstrated for verification of both steady and time-periodic electron diodes, as well as validation of radiation generated plasma in an end-radiated cylinder. In collaboration with Gregg Radtke, Sandia National Laboratories.

*Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. DOE's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

8:30

IW3 2 Understanding Plasmas with a High Degree of Correlation Through Modeling: From Rydberg and Fermionic Plasmas to Penning Plasmas*

ANDREW CHRISTLIEB, *Michigan State University*

Ultra cold neutral plasmas have gained attention over the past 15 years as being a unique environment for studying moderately to strongly coupled neutral systems. The first ultra cold neutral plasmas were generated by ionizing a Bose Einstein condensate, generating a plasma with .1K ions and 2-4K electrons. These neutral plasmas have the unique property that the ratio of their potential energy to their kinetic energy, ($\Gamma = PE/KE$), can greatly exceed 1, leading to a strongly correlated system. The high degree of correlation means that everything from wave propagation through collision dynamics behaves quite differently from their counterpart in traditional neutral plasmas. Currently, a range of gases and different methods for cooling have been used to generate these plasmas from supersonic expansion, through penning trap configurations (reference Tom, Jake and Ed). These systems have time scales form picoseconds to milliseconds have a particle numbers from 10^5 to 10^9. These systems present a unique environment for studying the physics of correlation due to their low particle number and small size. We start by reviewing ultra cold plasmas and the current sate of the art in generating these correlated systems. Then we introduce the methods we will use for exploring these systems through direct simulation of Molecular Dynamics models; Momentum Dependent Potentials, Treecodes and Particle-Particle Particle-Mesh methods. We use these tools to look at two key areas of ultra cold plasmas; development of methods to generate a plasma with a $\Gamma \gg 1$ and the impact of correlation of collisional relaxation. Our eventual goal is to use what we learn to develop models that can simulate correlation in large plasma systems that are outside of the scope of Molecular Dynamics models. In collaboration with Gautham Dharmuman, Mayur Jain, Michael Murillo and John Verboncoeur.

*This work it supposed by Air Force Office of Scientific Research.

Contributed Papers

9:00

IW3 3 Bridging the Gap between Global Models and Full Fluid Models in Electronegative Plasmas* ANDREW HURLBATT, TIMO GANS, DEBORAH O'CONNELL, *York Plasma Institute, Department of Physics, University of York, Heslington, York, YO10 5DD* The value of analytical and numerical models has been proven many times over. They allow investigation of complicated discharge phenomena and the interplay that makes plasmas such a complex environment. Global Models are quick to implement and can have almost negligible computation cost, however only approximate bulk values. Fluid Models take longer to develop, and can take days to solve, but provide spatial profiles. The work presented here details a different type of model, analytically similar to Fluid Models, but computationally closer to a Global Model, and extended to give solutions for the challenging environment of electronegative plasmas. Also included are non-isothermal electrons, gas heating, and coupled neutral dynamics. Solutions are reached in minutes, and spatial profiles are given for densities, fluxes, and temperatures. This allows broad parameter sweeps that are not practical with more costly models, as well as exposing non-trivial trends that Global Models do not capture. Examples are given for a low pressure oxygen CCP. Excellent agreement is shown with a Fluid Model, and the limitations of the corresponding Global Model are demonstrated. Applicability to other systems is discussed, particularly Narrow Gap discharges, where spatial non-uniformity is high.

*EPSRC EP/K018388/1.

9:15

IW3 4 Application of ILDM for Simplifying Complex Plasma Chemistry TAFIZUR REHMAN, KIM PEERENBOOM, *Department of Applied Physics, Eindhoven university of Technology, Eindhoven, The Netherlands* EFE KEMANECI, *Ruhr university Bochum, Theoretical Electrical Engineering, Bochum, Germany* WOUTER GRAEF, JAN VAN DIJK, *Department of Applied Physics, Eindhoven university of Technology, Eindhoven, The Netherlands* Numerical simulation of plasma models involving large numbers of species and reactions is computationally very expensive. One of the solutions to overcome the problem due to complex chemistry is to employ Chemical Reduction Techniques(CRT) used in combustion research. The CRT we apply here is ILDM (Intrinsic Low Dimensional Manifold). ILDM simply uses the fact that, due to wildly varying time scales, the reaction system is not evenly sensitive to all the reactions but some reactions are very fast and attain steady state in a very short interval of time. Based on this information ILDM method finds the lower dimensional space (manifold) inside a complete state-space such that after a short interval of time the fast time scales of the system will quickly move onto this low dimensional manifold and the full system description can be given by this lower dimensional manifold. By constructing the low dimensional manifold the reaction space is described in terms of only a few parameters and it becomes possible to tabulate the results in terms of those few parameters. By generating the look-up table, for given values of controlling parameters the remaining parameters are found explicitly. In this work we apply the ILDM method for the reduced simulation of an argon plasma.

SESSION IW4: ELECTRON AND PHOTON COLLISIONS
Wednesday Morning, 14 October 2015; Room: 303 AB at 8:00; James Williams, University of Western Australia, presiding

Invited Papers

8:00
IW4 1 Chiral Sensitivity in Electron-Molecule Interactions*
JOAN DREILING, *National Institute of Standards and Technology, Gaithersburg, MD*

All molecular forms of life possess a chiral asymmetry, with amino acids and sugars found respectively in L- and D-enantiomers only. The primordial origin of this enantiomeric excess is unknown. One possible explanation is given by the Vester- Ulbricht hypothesis [1], which suggests that left-handed electrons present in beta-radiation, produced by parity-violating weak decays, interacted with biological precursors and preferentially destroyed one of the two enantiomers. Experimental tests of this idea have thus far yielded inconclusive results [2]. We show direct evidence for chirally-dependent bond breaking through a dissociative electron attachment (DEA) reaction when spin-polarized electrons are incident on gas-phase chiral molecules [3]. This provides unambiguous evidence for a well-defined, chirally-sensitive destructive molecular process and, as such, circumstantial evidence for the Vester-Ulbricht hypothesis. I will also present the results of our systematic study of the DEA asymmetry for different chiral halocamphor molecules. Three halocamphor molecules were investigated: 3-bromocamphor ($C_{10}H_{15}BrO$), 3-iodocamphor ($C_{10}H_{15}IO$), and 10-iodocamphor. The DEA asymmetries collected for bromocamphor and iodocamphor are qualitatively different, suggesting that the atomic number of the heaviest atom in the molecule plays a crucial role in the asymmetric interactions. The DEA asymmetry data for 3- and 10-iodocamphor have the same qualitative behavior, but the 10-iodocamphor asymmetry is about twice as large at the lowest energies investigated, so the location of the heavy atom in the camphor molecule also affects the asymmetries. This work was performed at the University of Nebraska-Lincoln.

*This project is funded by NSF Grant PHY-1206067.

[1]T. L. V. Ulbricht and F. Vester, Tetrahedron **18**, 629 (1962).
[2]See, e.g, W. A. Bonner, Chirality **12**, 114 (2000).
[3]J. M. Dreiling and T. J. Gay, Phys. Rev. Lett. **113**, 1181 (2014).

8:30
IW4 2 Effects of polarization direction on laser-assisted free-free scattering*
BRUNO DEHARAK, *Illinois Wesleyan Univ*

This work will detail the effects of laser polarization direction (relative to the momentum transfer direction) on laser-assisted free-free scattering. Experimental results will be presented for electron-helium scattering in the presence of an Nd:YAG laser field ($h\nu = 1.17$ eV) where the polarization direction was varied both in, and out of, the scattering plane. To date, all of our experimental results are well described by the Kroll-Watson [1] approximation (KWA). The good agreement between our experiments and calculations using the KWA includes the case where the polarization is perpendicular to the momentum transfer direction, for which the KWA predicts vanishing cross section; other workers have found that the KWA tends to be inaccurate for cases where it predicts small cross sections [2]. We also present simulations of the effects that multiple scattering might have on experimental measurements.

*This work was supported by the United States National Science Foundation under Grant Number PHY-1402899.

[1]N. M. Kroll and K. M. Watson, Phys. Rev. A **8**, 804 (1973).
[2]e.g., M. O. Musa, A. MacDonald, L. Tidswell, J. Holmes, and B. Wallbank, J. Phys. B **43**, 175201 (2010).

Contributed Papers

9:00
IW4 3 What can the measurement of the transverse velocity of atoms tell us about strong-field interactions with atoms?
ROBERT SANG, *Centre for Quantum Dynamics, Griffith University* IGOR IVANOV, *Centre for Relativistic Laser Science, Institute for Basic Science* ANATOLI KHEIFETS, *Australian National University* JAME CALVERT, XIAOSHAN WANG, HAN XU, ADAM PALMER, DAVE KIELPINSKI, IGOR LITVINYUK, *Centre for Quantum Dynamics, Griffith University* In this paper we present a theoretical and experimental investigation of the ionization of atoms though the interaction of light in the strong-field regime. We show that the measurement of the transverse electron momentum distribution of ionised atoms as a function of the ellipticity of the ionizing light in the over-the-barrier and the tunnelling

regime evolve in qualitatively different ways and in the case of the use of linearly polarized light demonstrates that the strong-field approximation is not valid.

9:15

IW4 4 Stopping and Coulomb explosion of energetic carbon clusters in a plasma irradiated by an intense laser field* GUIQIU WANG, *Dalian Maritime University* YOUNIAN WANG, *Dalian University of Technology* The interaction of a charged particle beam with a plasma is a very important subject of relevance for many fields of physics, such as inertial confinement fusion (ICF) driven by ion or electron beams, high energy density physics, and related astrophysical problems. Recently, a promising ICF scheme has been proposed, in which the plasma target is irradiated simultaneously by intense laser and ion beams. For molecular ion or cluster, slowing down process will company the Coulomb explosion phenomenon. In this paper, we present a study of the effects of intense radiation field (RF) on the interaction of energetic carbon clusters in a plasma. The emphasis is laid on the dynamic polarization and correlation effects of the constituent ions within the cluster in order to disclose the role of the vicinage effects on the Coulomb explosion and energy deposition of the clusters in plasma. On the other hand, affecting of a strong laser field on the cluster propagating in plasma is considered, the influence of a large range of laser parameters and plasma parameters on the Coulomb explosion and stopping power are discussed.

*This work is supported by the National Natural Science Foundation of China (11375034), and the Fundamental Research Funds for the Central Universities of China (3132015144, 3132014337).

SESSION JW1: GEC & ICRP PLENARY SESSIONS, BUSINESS MEETING

Wednesday Morning, 14 October 2015; Room: 311 at 10:00; Hirotaka Toyoda Mirko Vukovic, Nagoya University TEL Technology Center America, presiding

WEDNESDAY MORNING \ JW1

Invited Papers

10:00

JW1 1 Plasma-surface interactions for top-down and bottom-up nanofabrication
KOUICHI ONO, *Kyoto University*

Plasma processing is now widely employed for the fabrication of nanostructures in diverse fields of micro/nanoelectronic, optoelectronic, energy conversion, and sensing devices. The top-down plasma processes are indispensable in today's microelectronics industry, relying on the use of primarily anisotropic plasma etching following the lithography to define mask patterns; in some cases, self-assembled masks are served for the subsequent etching. The bottom-up ones are often employed to synthesize nanostructures such as nanotubes and nanowires, relying on the use of plasma enhanced chemical vapor deposition and plasma sputtering on self-assembled as well as lithographically formed patterns of metal catalysts. Moreover, the mask-less top-down approaches have recently been demonstrated to form nanopillars and periodic nanoripples, and the catalyst-free bottom-up approaches have been demonstrated to form nanowires. This talk is concerned with the current understanding and future prospects for plasma-surface interactions responsible for these top-down and bottom-up plasma nanofabrication processes, with attention placed on the fabrication of nanoscale fins and gates and also nanowires of silicon. On nanometer scale, ions and neutrals incident on surfaces are few in number during processing; thus, the nanoscale plasma-surface interactions concerned are stochastic, owing to the temporal as well as spatial uniformity of the incident flux and angle of them on surfaces being processed at nanoscale.

11:00

JW1 2 The Gaseous Electronics Conference in its seventh decade: some new problems in an old field*
TIMOTHY GAY, *University of Nebraska*

Our understanding of scattering processes involving atoms and molecules is the foundation of the science of gaseous electronics. As fields of physics and chemistry, both atomic and molecular collisions and gaseous electronics originated in the early 20th century, and they have developed symbiotically and in parallel since then. Despite a century of progress since the Franck-Hertz experiment however, it is fair to say that the field of atomic and molecular collisions is old and well-explored, but not mature. While the electron-atomic hydrogen problem has been solved in complete detail [1], there are large regions in the "great outback" of the periodic table where either theory or experiment (or both) are nonexistent, or there is little correlation between the two. The problem becomes dramatically worse with molecules, including those with just one atom too many [2]. As applications of gaseous electronics have become both more sophisticated and more complicated, the demands for basic, accurate cross section data, especially for heavy, polyatomic molecular constituents, have escalated accordingly. This talk will review the status of our theoretical understanding of atomic and molecular collisions, and will present several case studies involving targets of He, H_2, Zn, H_2O, and $C_{10}H_{15}IO$ to illustrate current problems in the field. We will also consider crucial needs for basic collisional data in recent applied plasma science problems [3].

*Work supported by the NSF through Grant PHY-1505794.

[1]T. N. Rescigno, M. Baertschy, W. A. Isaacs, and C. W. McCurdy, Science **286**, 2474 (1999).
[2]J. W. Maseberg, K. Bartschat, and T. J. Gay, Phys. Rev. Lett. **111**, 253201 (2013).
[3]See. e.g., N. Mason, http://meetings.aps.org/link/BAPS.2013.GEC.ET5.2

Contributed Papers

12:00
JW1 3 GEC Business Meeting

SESSION KW1: PLASMA GAS CONVERSION
Wednesday Afternoon, 14 October 2015; Room: 301 B at 13:30; Osamu Sakai, University of Shiga Prefecture, presiding

Invited Papers

13:30
KW1 1 Plasmolysis for efficient CO_2-to-fuel conversion
GERARD VAN ROOIJ, *Dutch Institute For Fundamental Energy Research, Eindhoven, Netherlands*

The strong non-equilibrium conditions provided by the plasma phase offer the opportunity to beat traditional thermal process energy efficiencies via preferential excitation of molecular vibrational modes. It is therefore a promising option for creating artificial solar fuels from CO_2 as raw material using (intermittently available) sustainable energy surpluses, which can easily be deployed within the present infrastructure for conventional fossil fuels. In this presentation, a common microwave reactor approach is evaluated experimentally with Rayleigh scattering and Fourier transform infrared spectroscopy to assess gas temperatures and conversion degrees, respectively. The results are interpreted on basis of estimates of the plasma dynamics obtained with electron energy distribution functions calculated with a Boltzmann solver. It indicates that the intrinsic electron energies are higher than is favourable for preferential vibrational excitation due to dissociative excitation, which causes thermodynamic equilibrium chemistry still to dominate the initial experiments. Novel reactor approaches are proposed to tailor the plasma dynamics to achieve the non-equilibrium in which vibrational excitation is dominant. In collaboration with Dirk van den Bekerom, Niek den Harder, Teofil Minea, Dutch Institute For Fundamental Energy Research, Eindhoven, Netherlands; Gield Berden, Institute for Molecules and Materials, FELIX facility, Radboud University, Nijmegen, Netherlands; Richard Engeln, Applied Physics, Plasma en Materials Processing, Eindhoven University of Technology; and Waldo Bongers, Martijn Graswinckel, Erwin Zoethout, Richard van de Sanden, Dutch Institute For Fundamental Energy Research, Eindhoven, Netherlands.

Contributed Papers

14:00
KW1 2 Student Award Finalist: Transient Analysis of Pulsed Dry Methane Reforming in DBD-Catalyst Hybrid Reaction KEISHIRO TAMURA, SEIGO KAMESHIMA, YUTARO ISHIBASHI, RYO MIZUKAMI, TAKUMI YAMAZAKI, TOMOHIRO NOZAKI, *Tokyo Institute of Technology* Pulsed dry methane reforming in DBD-catalyst hybrid reaction was investigated. Optical emission spectroscopy was also employed for the better understanding of reaction mechanism for enhanced CH4 and CO_2 conversion as well as carbon removal reaction. Strong emission from C2 high pressure Swan system was uniquely observed when the Boudouard reaction dominates the surface reaction: C2 molecules were selectively produced via vibrationally excited CO which is originated from the adsorbed carbon on the catalysts. Time dependent change in gas composition and optical emission profiles of CO Ångström and C2 high pressure Swan systems were correlated in a systematic and consistent manner, leading to the deep insight into the CH4 and CO_2 activation mechanisms over solid catalysts. Moreover, individual contribution of radical injection and heat generated by DBD were investigated. The result clearly showed that the CH4 and CO_2 conversion rates were increased essentially by the radical injection, not the thermal effect of DBD.

14:15
KW1 3 NH3 reforming by DBD using a H2 permeable membrane YUKIO HAYAKAWA, SHINJI KAMBARA, *Gifu Univ* TOMONORI MIURA, *Sawafuji Electric Co., LTD.* GIFU UNIV. TEAM, SAWAFUJI ELECTRIC CO., LTD. COLLABORATION Ammonia is a hydrogen storage material that may solve several problems related to hydrogen transportation and storage in the hydrogen society. Catalytic thermal decomposition is a promising technique for producing hydrogen from ammonia. This study investigated atmospheric plasma decomposition as a new hydrogen production device. Therefore, it also observed that molecular ammonia was rapidly decomposed by electron energy in the plasma and was converted into molecular hydrogen. The hydrogen production was increased by the ammonia concentration, but hydrogen conversion was dramatically decreased to 13.9%, so unreacted ammonia was existed. In order to improve these problems, we developed a new high voltage electrode which was equipped with a hydrogen permeable membrane. At the result, this device could make high purity hydrogen at room temperature and unreacted ammonia was removed.

14:30
KW1 4 Preliminary Characterization of a Coaxial DBD Plasma-Catalytic Converter for Methane Partial Oxidation* SYLVAIN

COULOMBE, PABLO DIAZ GOMEZ MAQUEO, MATHEW EVANS, FLORENT SAINCT, JEFF BERGTHORSON, *McGill Univ* This contribution discusses the development and characteristics of a coaxial dielectric barrier discharge (DBD) using a methane-oxygen mixture at atmospheric conditions of temperature and pressure. A sinusoidal voltage waveform of 12 kVp-p at 20 kHz produces discharges in a 1.15 mm gap. Power is estimated using a Lissajous figure method while optical emission spectroscopy (OES) is used to estimate the rotational and vibrational temperatures of the gas. Obtained OES spectra are similar, differing mainly on the intensity of their CH and OH bands, tending towards a more intense OH band as oxygen availability increased. CH bands show the strongest emission intensities of which, CH(C-X) seems to be the most intense of all, followed by CH(A-X) and lastly by CH(B-X). The spectra of CH(A-X) and CH(C-X) were uploaded into a simulation software to estimate the plasma temperatures. For the CH(A-X) bands, a simulation with a $T_{rot} = 600$ K and a $T_{vib} = 6000$ K matched the experimental spectra. In the case of the CH(C-X) band, a $T_{rot} = 800$ K and a $T_{vib} = 4000$ K were determined. The vibrational temperatures are especially high, a result which is particularly important for the development of a plasma-catalysis reactor.

*The authors acknowledge the financial support provided by NSERC, FRQNT as well as McGill University through the McGill Engineering Doctoral Award program.

14:45

KW1 5 Methane reforming in a temperature-controlled DBD reactor DMITRY LEVKO, LAXMINARAYAN RAJA, *The University of Texas at Austin* Methane and carbon dioxide are among the main products of human activity. Therefore, they are considered among greenhouse gases, which may cause the global warming. On the other hand, methane is widely used in everyday life as an energy source and in industry for the synthesis of different chemicals. In order to utilize greenhouse gases or to generate chemicals from methane, one needs first to dissociate it. Then, this gas converts into desired products such as methanol, gasoline, syn-gas etc. Nowadays, there are several methods for CH_4 conversion. Steam reforming, partial oxidation, thermal and non-thermal plasmas are among them. During the last decades, the use of non-thermal plasma for methane reforming attracts more and more attention. This is caused by the possibility to control the process of methane conversion as well as the gas component content at the reactor outlet. In addition, the use of non-thermal plasma facilitates the control of reactor start up. The goal of the present work is the deep understanding of the plasma chemical processes accompanying the methane-air conversion in a temperature-controlled DBD reactor. To do this, we have developed the kinetic mechanism of $CH_4/N_2/O_2$ conversion for the gas temperature range 300-800 K and applied it to the global model.

15:00

KW1 6 Investigation of atmospheric pressure streamer discharges for methane reforming M.V. PACHUILO, F. STEFANI, L.A. ROSOCHA, L.L. RAJA, *University of Texas* Hydrogen has several valuable uses in transportation: it can lower the coefficient of variation under lean burn conditions in internal combustion engines, and it is essential for the operation of fuel cells. Currently hydrogen can only be produced efficiently by reducing fossil fuels in large facilities. However, on-board production is desirable to reduce the infrastructure associated with storing and distributing hydrogen. Plasma dry reforming processes are viable candidates for onboard production. Our current work investigates the fundamental behavior of a single streamer discharge in methane. The electron temperature, and active species generation are determined through time resolved spectroscopy. This work will hopefully accelerate the development of non-thermal plasma based devices that include: dielectric barrier discharges, pulsed corona discharges, and other atmospheric-pressure plasma devices.

15:15

KW1 7 Dependence of MnOx Catalyst Position on Toluene Decomposition using Nanosecond Pulsed Discharge Plasma JUNKAI HAN, AKIHIKO OGASAWARA, *Kumamoto University* JINLONG WANG, *Tsinghua University* DOUYAN WANG, TAKAO NAMIHIRA, MITSURU SASAKI, HIDENORI AKIYAMA, *Kumamoto University* PENGYI ZHANG, *Tsinghua University* KUMAMOTO UNIVERSITY COLLABORATION, TSINGHUA UNIVERSITY COLLABORATION Plasma catalysis, which combines advantages of high selectivity due to the catalysis and with fast ignition and response due to plasma technique, appears to be a promising technology to simultaneously resolve both efficiency and workability issues. In practice, a catalyst can be combined with NTP in two ways: by introducing the catalyst in the discharge zone (in-plasma catalytic reactor) or by placing the catalyst after the discharge zone (post-plasma catalytic reactor). This work aims to clarify combined effects by coupling MnOx catalyst with ns pulsed discharge system for decomposition of 100 ppm toluene utilizing three methods: plasma alone, in-plasma catalytic and post-plasma catalytic methods, in atmospheric pressure at room temperature. As the results, toluene removal ratio reached 100% at approximately 50 J/L under the in-plasma catalytic and post-plasma catalytic methods, while it was 70% under the plasma alone method. The concentrations of O_3, HCOOH, and CO under the plasma alone method were higher compared with the in-plasma catalytic or post-plasma catalytic methods. CO_2 selectivity under the post-plasma catalytic method was the highest of these three methods when toluene removal ratio exceeded 80%.

15:30

KW1 8 Development of High-speed and Environmentally Friendly Photoresist Removal Process using Pulsed Microwave Plasma in Water Vapor TATSUO ISHIJIMA, TAKUYA KITANO, TAKUYA ITO, HIROAKI SUZUKI, YASUNORI TANAKA, YOSHIHIKO UESUGI, *Kanazawa University* TAKASHI NISHIYAMA, HIDEO HORIBE, *Osaka City University* A novel photoresist removing technique using a pulsed microwave excited plasma produced in vaporized water bubble (MWBP) has remarkable properties such as environmentally-friendly and low temperature process. This photoresist removal method has been studied to apply a practical semiconductor manufacturing process. On the other hand, the minimal-fabrication system (minimal-fab) without using a clean room has been proposed and developed in order to adapt a high-variety low-volume semiconductor manufacturing process. Recently MOS device production has been succeeded using the minimal-fab. It is expected to evaluate the proposed MWBP ashing technology ability and clarify the possibility for a practical semiconductor manufacturing process to be incorporated in the minimal-fab. In order to apply MWBP for the minimal-fab, reduction of the input microwave power is necessary because the size of the minimal-fab is a compact and is highly standardized to maximize the convenience of the fabrication system utilization. In this study, we have investigated MWBP production methods to reduce the MWBP production power. We found that the decrease in the MWBP production power can be achieved by introducing a new bubble-control-structure to keep the bubble around the microwave antenna.

SESSION KW2: MAGNETICALLY ENHANCED PLASMAS
Wednesday Afternoon, 14 October 2015; Room: 308 AB at 13:30; Tim Gans, York University, presiding

Invited Papers

13:30
KW2 1 Fundamental Study on Filter Effect of Confronting Divergent Magnetic Fields Applied to a Low-Pressure Inductively Coupled Plasma*
HIROTAKE SUGAWARA, *Hokkaido University*

Function of confronting divergent magnetic fields (CDMFs) applied to an inductively coupled plasma called the X-point plasma [1] was investigated. The plasma is driven by a planar spiral rf antenna on the top of a cylindrical chamber. The CDMFs are induced by two coaxial coils with dc currents of opposite directions, and have cusps on their separatrix plane and a magnetic null point at its center. Electron motion in H_2 at 1 Pa under the CDMFs was simulated using a Monte Carlo method. Electrons released form the chamber ceiling were captured in the upper region of the chamber by magnetic flux lines running between the ceiling and side wall. However, some of them diffused downward across the separatrix in two ways: passage through the weak magnetic field around the center, and displacement of electron gyrocenters from the upper region to the lower region due to scattering by gas molecules near the outer part of the separatrix. While the former was unselective about electron energy, the latter tended to occur for high-energy electrons with long gyroradii. This position-dependent selectivity in electron passage across the separatrix indicates applicability of the CDMFs as a magnetic filter or shutter.

*Work supported by JSPS KAKENHI Grant Number 25400528.

[1]T. Tsankov and U. Czarnetzki, IEEE Trans. Plasma Sci. **39**, 2538 (2011).

Contributed Papers

14:00
KW2 2 Microwave Assisted Helicon Plasmas EARL SCIME, UMAIR SIDDIQUI, JOHN MCKEE, ZACH SHORT, JULIANNE MCILVAIN, *West Virginia University* Up to 1.2 kW of pulsed 2.45 GHz microwaves are injected into argon and helium helicon plasmas at 6 to 20 mTorr neutral pressure, at 500 W of continuous rf power, and up to 1 kG magnetic field strengths. The objective is to heat the tail of the electron energy distribution function (EEDF) and populate ion metastable states for investigation with laser-induced-fluorescence. Langmuir probes are used to measure the EEDF and optical emission spectroscopy is used to monitor ion emission from excited states populated by the additional microwave power. The injection of microwave power in argon helicon plasmas is shown to heat the high energy tail of the EEDF without increasing the plasma density. Argon ion emission is shown to increase by a factor of 4. Injection of microwaves into a helium helicon plasma is shown to cool the bulk of the EEDF and increase the plasma density. Previously absent helium ion emission lines are observed with the injection of microwaves.

14:15
KW2 3 Negative hydrogen ions in a linear helicon plasma device* CORMAC CORR, JESSE SANTOSO, CAMERON SAMUELL, *Australian National University* HANNAH WILLETT, *University of York* ROUNAK MANOHARAN, SEAN O'BYRNE, *The University of New South Wales* Low-pressure negative ion sources are of crucial importance to the development of high-energy (>1 MeV) neutral beam injection systems for the ITER experimental tokamak device. Due to their high power coupling efficiency and high plasma densities, helicon devices may be able to reduce power requirements and potentially remove the need for caesium. In helicon sources, the RF power can be coupled efficiently into the plasma and it has been previously observed that the application of a small magnetic field can lead to a significant increase in the plasma density. In this work, we investigate negative ion dynamics in a high-power (20 kW) helicon plasma source. The negative ion fraction is measured by probe-based laser photodetachment, electron density and temperature are determined by a Langmuir probe and tuneable diode laser absorption spectroscopy is used to determine the density of the H(n = 2) excited atomic state and the gas temperature. The negative ion density and excited atomic hydrogen density display a maximum at a low applied magnetic field of 3 mT, while the electron temperature displays a minimum. The negative ion density can be increased by a factor of 8 with the application of the magnetic field. Spatial and temporal measurements will also be presented.

*The Australian Research Grants Council is acknowledged for funding.

14:30
KW2 4 Analysis of Electron Trajectories in Magnetized High Power Plasmas* DENNIS KRUEGER, SARA GALLIAN, JAN TRIESCHMANN, RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Germany* High Power Impulse Magnetron Sputtering (HiPIMS) is an important example of magnetized technological plasmas. With HiPIMS the focus lies on the generation of a high density plasma with a remarkably high degree of ionization [1]. It can be used for the deposition of thin films with superior density and quality. Theoretical approaches to the regime of magnetized low temperature plasmas encounter some fundamental difficulties, for example concerning the details of the magnetic field configuration, the strongly varying degree of magnetization, and the frequent wall interactions. A kinetic single particle model is used for the investigations. Single electron trajectories are analyzed with the widely used Boris algorithm [2] within the magnetized zone above the target (racetrack). We further examine a configuration where symmetry breaking occurs due to a potential bump, which is rotating azimuthally around the racetrack (spoke). Observing the effects of this structure on the single electron motion may allow us to obtain further insight into this phenomenon.

*This work is supported by the German Research Foundation in the frame of the Collaborative Research Centre TRR 87.

[1]J. T. Gudmundsson *et al.*, J. Vac. Sci. Technol. A **30**, 030801 (2012).
[2]J. P. Boris, Proc. 4th Conf. Num. Sim. Plasmas, 3–67 (1970).

14:45
KW2 5 Observation of helicon wave with m = 0 antenna in a weakly magnetized inductively coupled plasma source BERT ELLINGBOE, NISHANT SIRSE, RACHEL MOLONEY, JOHN MCCARTHY, *Dublin City University, Ireland* Bounded whistler wave, called "helicon wave," is known to produce high-density plasmas and has been exploited as a high density plasma source for many applications, including electric propulsion for spacecraft. In a helicon plasma source, an antenna wrapped around the magnetized plasma column launches a low frequency wave, $\omega_{ce}/2 > \omega_{\text{helicon}} > \omega_{ce}/100$, in the plasma which is responsible for maintaining high density plasma. Several antenna designs have been proposed in order to match efficiently the wave modes. In our experiment, helicon wave mode is observed using an m = 0 antenna. A floating B dot probe, compensated to the capacitively coupled E field, is employed to measure axial-wave-field-profiles (z, r, and θ components) in the plasma at multiple radial positions as a function of rf power and pressure. The B_θ component of the rf-field is observed to be unaffected as the wave propagates in the axial direction. Power coupling between the antenna and the plasma column is identified and agrees with the E, H, and wave coupling regimes previously seen in M=1 antenna systems. That is, the B_z component of the rf-field is observed at low plasma density as the B_z component from the antenna penetrates the plasma. The B_z component becomes very small at medium density due to shielding at the centre of the plasma column; however, with increasing density, a sudden "jump" occurs in the B_z component above which a standing wave under the antenna with a propagating wave away from the antenna are observed.

15:00
KW2 6 Spatial and temporal evolution of negative ions in a pulsed inductively coupled hydrogen plasma source across a magnetic filter STUART NULTY, CORMAC CORR, *Australian Natl Univ* Low-temperature electronegative plasmas have important applications in high-energy sources for fusion energy, plasma thrusters and materials processing. Neutral beam injection systems and space thruster technology such as the PEGASUS propulsion system rely on efficiently producing extractable negative ions. In this work we investigate the production of hydrogen negative ions in a pulsed inductively coupled plasma across a magnetic filter. The electron energy distribution function, plasma density and electron temperature are determined using an RF compensated Langmuir probe, and time-resolved laser photo-detachment is used to measure the negative ion fraction. The spatial and temporal evolution of these plasma parameters within the plasma source will be presented. Using a pulsed plasma and a magnetic filter, the electron temperature can be efficiently controlled and a higher density of negative ions compared to electrons can be obtained at certain locations within the source.

15:15
KW2 7 Coupling modes in a dipolar microwave plasma source ANA LACOSTE, PIERRE BAELE, REMY MAURAU, STEPHANE BECHU, ALEXANDRE BES, *LPSC, Université Grenoble Alpes, CNRS/IN2P3, 53 rue des Martyrs, 38026 Grenoble Cedex, France* The multi-dipolar microwave plasma is a suitable technology for the scaling-up of high density plasma processing in the very low pressure range. Effectively, a large area or volume of plasma can be achieved by a mere distribution, over 2 or 3 dimensions, of a number of elementary plasma sources. To enhance the microwave coupling efficiency and optimize the spatial repartition of the elementary plasma sources, it could be helpful to localize the production regions and coupling modes that govern the energy transfer from the wave to the electrons. The main objective of this work is to identify the possible coupling modes as a function of operating parameters. Accordingly, the plasma parameters (electron temperature, density) were correlated together with the electromagnetic radiation, as well as with different coupling modes observed as a function of microwave power. High plasma densities, up to 10 times the critical density (for one source), can be achieved through an efficient transfer of the electrostatic wave energy to the electrons.

SESSION KW3: MODELING AND SIMULATION II
Wednesday Afternoon, 14 October 2015; Room: 305 AB at 13:30; Christopher Moore, Sandia National Laboratories, presiding

Invited Papers

13:30
KW3 1 Heavy particle transport in sputtering systems*
JAN TRIESCHMANN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Germany*

This contribution aims to discuss the theoretical background of heavy particle transport in plasma sputtering systems such as direct current magnetron sputtering (dcMS), high power impulse magnetron sputtering (HiPIMS), or multi frequency capacitively coupled plasmas (MFCCP). Due to inherently low process pressures below one Pa only kinetic simulation models are suitable. In this work a model appropriate for the description of the transport of film forming particles sputtered of a target material has been devised within the frame of the OpenFOAM [1] software (specifically dsmcFoam [2]). The three dimensional model comprises of ejection of sputtered particles into the reactor chamber, their collisional transport through the volume, as well as deposition of the latter onto the surrounding surfaces (i.e. substrates, walls). An angular dependent Thompson energy distribution [3] fitted to results from Monte-Carlo simulations is assumed initially. Binary collisions are treated via the M1 collision model [4], a modified variable hard sphere (VHS) model. The dynamics of sputtered and background gas species can be resolved self-consistently following the direct simulation Monte-Carlo (DSMC) approach or, whenever possible, simplified based on the test particle method (TPM) with the assumption of a constant, non-stationary background at a given temperature. At the example of an MFCCP research reactor the transport of sputtered aluminum is specifically discussed. For the peculiar configuration and under typical process conditions with argon as process gas the transport of aluminum sputtered of a circular target is shown to be governed by a one dimensional interaction of the imposed and backscattered particle fluxes. The results are analyzed and discussed on the basis of the obtained velocity distribution functions (VDF).

*This work is supported by the German Research Foundation (DFG) in the frame of the Collaborative Research Centre TRR 87.

[1]OpenFOAM, www.openfoam.org.
[2]T. J. Scanlon *et al.*, Comp. Fluids **39**, 2078 (2010).
[3]M. Stepanova and S. K. Dew, J. Vac. Sci. Technol. A **19**, 2805 (2001).
[4]A. Kersch *et al.*, J. Appl. Phys. **75**, 2278 (1994).

Contributed Papers

14:00

KW3 2 A Vlasov-BCA method for numerical simulations of the plasma sheath structure in presence of a material releasing wall DAVIDE CURRELI, RINAT KHAZIEV, SHANE KENILEY, STEVEN MARCINKO, *University of Illinois at Urbana Champaign* We present a coupled Vlasov-BCA (Binary Collision Approximation) method for the simulation of the plasma sheath in presence of a material-releasing wall. The method couples a Vlasov solver of a multi-species plasma with an improved version of the TRIDYN code including surface dynamic composition, multi-component targets, and surface roughness effects. The classical problem of defining proper boundary conditions into a Vlasov code is solved by using at the boundary distribution functions calculated thanks to the BCA module. A standard kernel smoother is adopted to control the noise level of the distributions predicted by the BCA. When solved in one dimension the method is computationally inexpensive and allows to resolve the plasma sheath structure in presence of material sputtering, backscattering, and implantation, for both mono-component and multi-component targets. From the moments of the distribution functions, the particle and heat fluxes of both the plasma and the material species can be easily derived.

14:15

KW3 3 A zero-equation turbulent electron transport model for cross-field migration and its implementation in a 2-D hybrid plasma Hall thruster simulation* MARK CAPPELLI, CHRIS YOUNG, EUSNUN CHA, *Stanford University* EDUARDO FERNANDEZ, *Eckerd College* STANFORD PLASMA PHYSICS LABORATORY COLLABORATION, ECKERD COLLEGE COLLABORATION We present a simple, zero-equation turbulence model for electron transport across the magnetic field of a plasma Hall thruster and integrate this model into 2-D hybrid particle-in-cell simulations of a 72 mm diameter laboratory thruster operating at 400 W. The turbulent transport model is based on the assumption that the primary means of electron energy dissipation is the turbulent eddy cascade in the electron fluid to smaller scales. Implementing the model into 2-D hybrid simulations is relatively straightforward and leverages the existing framework for solving the electron fluid equations. We find that the model captures the strong axial variation in the mobility seen in experiments. In particular, it predicts the existence of a strong transport barrier which anchors the region of plasma acceleration. The model also captures the time-averaged experimental discharge current and its fluctuations due to ionization instabilities. We observe quantitative agreement with recent laser induced fluorescence measurements of time-averaged xenon ion and neutral velocities along the channel centerline.

*This work was supported by the Air Force Office of Scientific Research.

14:30

KW3 4 Development Of Sputtering Models For Fluids-Based Plasma Simulation Codes* SETH VEITZER, KRISTIAN BECKWITH, PETER STOLTZ, *Tech-X Corporation* Rf-driven plasma devices such as ion sources and plasma processing devices for many industrial and research applications benefit from detailed numerical modeling. Simulation of these devices using explicit PIC codes is difficult due to inherent separations of time and spatial scales. One alternative type of model is fluid-based codes coupled with electromagnetics, that are applicable to modeling higher-density plasmas in the time domain, but can relax time step requirements. To accurately model plasma-surface processes, such as physical sputtering and secondary electron emission, kinetic particle models have been developed, where particles are emitted from a material surface due to plasma ion bombardment. In fluid models plasma properties are defined on a cell-by-cell basis, and distributions for individual particle properties are assumed. This adds a complexity to surface process modeling, which we describe here. We describe the implementation of sputtering models into the hydrodynamic plasma simulation code USim, as well as methods to improve the accuracy of fluids-based simulation of plasmas-surface interactions by better modeling of heat fluxes.

*This work was performed under the auspices of the Department of Energy, Office of Basic Energy Sciences Award #DE-SC0009585.

14:45

KW3 5 2D-Combined ICP/CCP numerical modeling for RF plasma source MASARU MIYASHITA, *Sumitomo Heavy Industries, Ltd.* KEI IKEDA, *ATHENASYS Ltd.* SYUTA OCHI, *Sumitomo Heavy Industries Ion Technology Co., Ltd.* A numerical investigation of sputtering distribution on antenna cover in Radio Frequency (13.56 MHz) plasma(RF plasma) source by energetic ions bombardment has been performed including influences of static electric field from voltage of antenna and of inductive electric field from current of antenna. In order to validate the developed technique, the static electron heating distribution and the inductive electron heating distribution in simulation are compared. The comparison shows the static electric field is shielded in the sheath of the high electron density ($10^{17}\mathrm{m}^{-3}$) plasma and the plasma is sustained by inductive electric field from current of antenna. The deep sheath potential in simulation is generated over the region of large vulnerable in experiment. The numerical simulation technique with calculating static electric field and inductive electric field is important for development of the RF plasma source with large current and long life time.

15:00

KW3 6 Plasma Characteristics for Curved Capacitive Source using Plasma Modeling KALLOL BERA, JOHN FORSTER, MANI SUBRAMANI, UMESH KELKAR, *Applied Materials, Inc.* Capacitively coupled plasma (CCP) in curved configuration has been investigated for plasma density and power deposition distribution using plasma modeling. In the CCP model, charged particle densities are determined by solving transport equations using drift-diffusion approximation. The electron temperature is solved using electron energy equation. The electric (scalar) potential is derived from Poisson equation. A semi-circular annular configuration consisting of inner curved surface as powered electrode and outer curved surface as grounded electrode is used. Ar plasma at moderate pressure (a few Torr) has been simulated at 13.56 MHz. A negative dc bias develops at the powered electrode that is smaller than grounded electrode. Stronger electric field leads to stronger power deposition and correspondingly higher plasma density near the powered electrode. As straight segments are added to the semi-circular configuration, it is found that plasma drifts away from the curved region to the straight region. Further addition of semi-circular and straight segments reduces DC bias to zero as the powered electrode and grounded electrode areas become equal. However, plasma is observed to be stronger near the straight region compared to curved region as plasma drifts away from the curved region to straight region.

15:15
KW3 7 Student Award Finalist: Advances in the three-dimensional simulation of streamer discharges* JANNIS TEUNISSEN, *Center for Mathematics and Computer Science (CWI), Amsterdam, The Netherlands* UTE EBERT, *Center for Mathematics and Computer Science (CWI), Amsterdam, The Netherlands and Eindhoven University of Technology* We have implemented a 2D and 3D streamer model inside AFiVO, a simulation framework that we have recently developed. We use numerical techniques such as adaptive mesh refinement, parallel multigrid and a novel implementation of photoionization to push simulations to new limits. This allows us to study the interaction of two streamers in 3D, the branching of streamers in 3D, or the propagation of a streamer over a dielectric surface. Simulations in 2D also benefit, allowing for a relatively interactive exploration of parameter regimes. We present highlights of the new simulation possibilities.

*JT acknowledges support from STW project 10755.

15:30
KW3 8 Pulsed surface discharges in nitrogen and in air: experiments and simulations* ANNA DUBINOVA, *Centrum Wiskunde en Informatica, Amsterdam, Netherlands* DIRK TRIENEKENS, *Eindhoven University of Technology, Eindhoven, Netherlands* UTE EBERT, *Centrum Wiskunde en Informatica, Amsterdam, Netherlands* SANDER NIJDAM, *Eindhoven University of Technology, Eindhoven, Netherlands* We study positive streamer discharges in nitrogen and in air propagating near or on the surface of a dielectric rod. The discharge is launched from a needle, and propagates towards a dielectric rod which is placed directly under the needle. In some cases, when the discharge attaches to the rod it moves along it with a velocity larger than in the gas without the rod, and in other cases it moves more slowly. We aim at understanding this dynamics of streamer interaction with dielectrics and the mechanisms of streamer propagation along the surface. We have developed a cylindrically symmetric model based on the fluid streamer model in local field approximation. Our model allows us to analyze the interplay of photoionization, photoelectron emission from the rod and dielectric polarization of the rod, and voltage pulse shape, amplitude and repetition frequency. We compare the morphology and the velocity of the simulated surface streamers with those measured in dedicated experiments. In the experiments, we use stroboscopic imaging with an ICCD camera to retrieve streamer velocity and shape.

*The work is supported by STW project 12119, partly sponsored by ABB.

SESSION KW4: ATMOSPHERIC & THERMAL PLASMAS
Wednesday Afternoon, 14 October 2015; Room: 303 AB at 13:30; Jochen Schein, Universität der Bundeswehr, presiding

Invited Papers

13:30
KW4 1 Modelling for turbulent transport of nanoparticles growing around a thermal plasma jet
MASAYA SHIGETA, *Osaka University*

Modelling works for expressing the simultaneous processes of growth and transport of nanoparticles around a turbulent-like thermal plasma jet are presented. From the physical aspect, extending the previous model, a simple-but-consistent model which requires less computational costs is developed to describe the nanoparticles' birth and collective growth through homogeneous nucleation, heterogeneous condensation, and coagulation among themselves as well as transports by convection, diffusion, and thermophoresis. From the mathematical aspect, an original simulation code with higher accuracy is developed to express thermal plasma turbulence and to capture steep gradients in the spatial distribution of nanoparticles. As a base case, an argon thermal plasma jet is ejected at 1.5 slm from the nozzle, and iron vapor is supplied at 0.1 g/min with the plasma jet. The computation shows that the high-temperature plasma jet entrains the surrounding non-ionized gas because of Kelvin-Helmholtz instability at their interface. The instability waves grow up and then the interface rolls up to eddies. As the jet goes downstream, the eddies break to smaller ones, which lead to turbulence transition. This feature has also been reported in the experimental study. The iron vapor is transported with the plasma flow and simultaneously diffuses across the plasma's fringe where the vapor experiences the temperature decrease. As a result, the vapor changes its phase to nanoparticles through nucleation and condensation. The nanoparticles are also transported by convection and diffusion. The regions of large diameters coincide with those of low number densities of nanoparticles, because the size of nanoparticles increases through coagulation among themselves decreasing their own numbers.

14:00
KW4 2 Diagnostics of transient non-equilibrium atmospheric pressure plasmas*
PETER BRUGGEMAN, *University of Minnesota*

Atmospheric pressure plasmas have received a renewed interest in last decades for a variety of applications ranging from environmental remediation, material processing and synthesis to envisioned medical applications such as wound healing. While most low pressure plasmas are diffuse, atmospheric pressure plasmas are often filamentary in nature. The existence of these filaments is correlated with strong gradients in plasma properties both in space and time that can significantly affect the plasma chemistry. As these filaments are often randomly appearing in space and time, it poses great challenges for diagnostics often requiring the stabilization of the filament to study the in situ plasma kinetics. In this contribution, diagnostics of a stabilized nanosecond pulsed plasma filament in a pin-pin geometry and a filament in a nanosecond pulsed atmospheric pressure plasma jet will be presented. We will focus on electron kinetics and OH and H radical production in water containing plasmas. The extension of these diagnostics to plasmas in liquids will also be discussed.

*The author acknowledges support from NSF PHYS1500135, Department of Energy Plasma Science Center through the U.S. Department of Energy, Office of Fusion Energy Sciences (Contract No. DE-SC0001939), University of Minnesota and STW (Netherlands).

Contributed Papers

14:30

KW4 3 MHD Simulations of Thermal Plasma Jets in Coaxial Plasma Accelerators VIVEK SUBRAMANIAM, LAXMINARAYAN RAJA, *The University of Texas at Austin* The development of a magneto-hydrodynamics (MHD) numerical tool to study high energy density thermal plasma in coaxial plasma accelerators is presented. The coaxial plasma accelerator is a device used simulate the conditions created at the confining wall of a thermonuclear fusion reactor during an edge localized mode (ELM) disruption event. This is achieved by creating magnetized thermal plasma in a coaxial volume which is then accelerated by the Lorentz force to form a high velocity plasma jet. The simulation tool developed solves the resistive MHD equation using a finite volume method (FVM) framework. The acceleration and subsequent demagnetization of the plasma as it travels down the length of the accelerator is simulated and shows good agreement with experiments [1]. Additionally, a model to study the thermalization of the plasma at the inlet is being developed in order to give self-consistent initial conditions to the MHD solver.

[1]H. Sitaraman and L. L. Raja, Magneto-hydrodynamics simulation Study of deflagration mode in co-axial plasma accelerators, Phys. Plasmas **21**, 012104 (2014).

14:45

KW4 4 Application of Atmospheric-Pressure Microwave Line Plasma for Low Temperature Process HARUKA SUZUKI, SUGURU NAKANO, *Nagoya Univ.* HITOSHI ITOH, *PLANT, Nagoya Univ., Tokyo Electron Ltd.* MAKOTO SEKINE, MASARU HORI, HIROTAKA TOYODA, *Nagoya Univ., PLANT, Nagoya Univ.* Atmospheric pressure (AP) plasmas have been given much attention because of its high cost benefit and a variety of possibilities for industrial applications. In various kinds of plasma production technique, pulsed-microwave discharge plasma using slot antenna is attractive due to its ability of high-density and stable plasma production. In this plasma source, however, size of the plasma has been limited up to a few cm in length due to standing wave inside a waveguide. To solve this, we have proposed a newly-developed AP microwave plasma source that utilizes not standing wave but travelling wave. By using this plasma source, spatially-uniform AP line plasma with 40 cm in length was realized by pure helium discharge in 60 cm slot and with nitrogen gas additive of 1%. Furthermore, gas temperature as low as 400 K was realized in this device. In this study, as an example of low temperature processes, hydrophilic treatment of PET films was performed. Processing speed increased with pulse frequency and a water contact angle of $\sim 20^{\circ}$ was easily obtained within 5 s with no thermal damage to the substrate. To evaluate treatment-uniformity of long line length, PET films were treated by 90 cm slot-antenna plasma and uniform treatment performance was confirmed.

15:00

KW4 5 High-Speed Visualization of Evaporation Phenomena from Tungsten Based Electrode in Multi-Phase AC Arc MANABU TANAKA, *Department of Chemical Engineering, Kyushu University* TARO HASHIZUME, TOMOYUKI IMATSUJI, YUSHI NAWATA, *Department of Chemical Systems and Engineering, Kyushu University* TAKAYUKI WATANABE, *Department of Chemical Engineering, Kyushu University* A multi-phase AC arc has been developed for applications in various fields of engineering because it possesses unique advantages such as high energy efficiency. However, understanding of fundamental phenomena in the multi-phase AC arc is still insufficient for practical use. Purpose of this study is to investigate electrode erosion mechanism by high-speed visualization of the electrode metal vapor in the arc. Results indicated that the electrode mainly evaporated at anodic period, leading to the arc constriction. Moreover, evaporation of W electrode with 2wt% La_2O_3 at the anodic period was much higher than that with 2wt% ThO_2. This can be explained by different properties of these oxide additives. Evaporation of the oxide additive resulted in the arc constriction, which accelerated the evaporation of W electrode. Therefore, addition of La_2O_3 with lower melting and boiling point than ThO_2 lead to stronger arc constriction, resulting in severer evaporation of W electrode.

15:15

KW4 6 Comparative Study on Extinction Process of Gas-Blasted Air and CO_2 Arc Discharge Using Two-Dimensional Electron Density Imaging Sensor YUKI INADA, TOMOKI KAMIYA, SHIGEYASU MATSUOKA, AKIKO KUMADA, HISATOSHI IKEDA, KUNIHIKO HIDAKA, *The University of Tokyo* TOMOYUKI NAKANO, KOSUKE MURAI, YASUNORI TANAKA, *Kanazawa University* TAKESHI SHINKAI, *Toshiba Corporation* Systematic comparison of the electron density images for various kinds of arc-quenching gas media inside high-voltage circuit breakers is a promising method for the effective search and development of SF6-alternative gases. However, electron density imaging over the decaying arcs around the nozzle throat of the circuit breakers is extremely difficult by using the conventional arc generation setup and localized type sensing systems, due to the nozzle opaqueness and spatiotemporal instability of long-gap arc discharges around current zero. Here, we achieved two-dimensional electron density imaging over the decaying arcs around the nozzle throat first in the world, by a combination of the development of a unique gas flow nozzle integrating a cubic quartz cell and the single-shot recordings using Shack-Hartmann sensors. Shack-Hartmann sensors were applied to gas-blasted air and CO_2 arc discharges under current-zero phases after sudden switch-off of stationary arc currents. These experimental results showed that the electron densities and arc diameters took the minimums in the upper stream nozzle regions with the maximum blasting gas speeds. In addition, CO2 had a shorter electron density decaying time constant than air, which is consistent with the previous theoretical studies on higher interruption performance of CO2 compared with air.

SESSION LW1: POSTER SESSION II (4:00pm - 6:00pm)
Wednesday Afternoon, 14 October 2015
Exhibit Exhibit Hall III at 16:00

LW1 1 CHARGED PARTICLE COLLISIONS II

LW1 2 Low energy elastic scattering from toluene* AHMAD SAKAAMINI, LEIGH HARGREAVES, MURTADHA A. KHAKOO, *Cal State Univ- Fullerton* DIEGO FARAGO PASTEGA, MARCIO H.F. BETTEGA, *U Federal do Parana, Brazil* Differential scattering cross sections for elastic scattering of low-energy electrons from toluene are presented in the form of experimental and theoretical (Schwinger multichannel method with pseudopotentials) results. The experimental incident electron energy range is from 1 eV to 20 eV and scattering angles from 15 to 130 degrees. Comparisons with other available cross sections are also presented.

*CSUF is funded by an NSF-PHY-RUI grant; U. Federal do Parana is funded by CNPq, CAPES and Finep.

LW1 3 Excitation of atmospheric species by electron impact* PAUL V. JOHNSON, *Jet Propulsion Laboratory* XIANMING LIU, *Space Environment Technologies* CHARLES P. MALONE, JEFFREY D. HEIN, *Jet Propulsion Laboratory* MURTADHA A. KHAKOO, *Cal State Fullerton* Electron collisions with atmospherically relevant neutral molecular targets, such as H_2 and N_2, have been investigated. Resulting fluorescence was probed using various monochromator-detector combinations, such that photon intensities were investigated as a function of wavelength and incident electron energy. In addition, electron energy-loss spectroscopy (EELS) was utilized such that differential cross sections (DCSs) and integral cross sections (ICSs) were obtained. The measured emission cross sections, DCSs, and ICSs, as well as calculations of spectroscopic parameters, for these atmospheric species will be presented.

*Support from NASA's PATM, HTIDS, and OPR Programs is gratefully acknowledged.

LW1 4 Low-energy electron impact excitation of ethanol LEIGH HARGREAVES, *Cal State Univ- Fullerton* KENNETH VARELLA, *Purdue University* MURTADHA KHAKOO, *Cal State Univ-Fullerton* CARL WINSTEAD, VINCE MCKOY, *California Institute of Technology* We present differential cross sections measurements for excitation of the four lowest-lying states of ethanol by low energy electrons. The measurements were obtained using an electron energy loss spectrometer with a moveable aperture gas source, and employing a least squares fitting routine to unfold the overlapping contributions of each transition in the measured spectra. Data was taken at scattering angles ranging from 15 – 130 degrees, and incident energies between 9 and 20 eV. The measurements are compared with current theoretical calculations, and previous results for excitation of methanol and water.

LW1 5 Polarized electron correlations near auto-ionizing states of zinc atoms JAMES WILLIAMS,* LUKA PRAVICA, SERGEY SAMARIN, *University of Western Australia* Multi-electron metal atoms find new applications in diverse structures with spin and momentum-dependent properties having significance in determining material functionalities. Electron correlations effects are determined from scattering kinematics of spin-polarized electrons exciting zinc atoms near autoionizing states up to 16 eV. Previous studies of the $4p^{3,1}P_1$, $4d,5d,6d^3D_{1,2,3}$ and $4d,5d^1D_1$ excited states observed photon decay intensities and scattered electron energies and angles in the energy region of the $3d^94s^24p$ autoionizing states up to 12 eV [1]. Strong electron correlations and active roles of $3d$ electrons were evident. Our observations of the 5^3S excited state for electron energies up to 16 eV show dominant $3d$ core-excited negative-ion resonances and strong Post-Collision Interaction (PCI). For low energies of scattered and ejected electrons, after near-threshold excitation of the $3d^94s^24p$ autoionizing states, a large transfer of orbital angular momentum is evident. Results include angular differential elastic scattering and excitation functions, "integrated" Stokes polarization parameters and spin up/down asymmetries indicating spin-orbit interaction and electron exchange effects.

*School of Physics

[1] S. Napier *et al.*, Phys. Rev. A **78**, 032706 (2008).

LW1 6 Electron ionization and ion-molecule reactions of triethylborane CHARLES JIAO, *UES* STEVEN ADAMS, *Air Force Research Laboratory* Triethylborane (TEB) is used as a radical initiator in many chemical reactions and as an excellent ignition source for jet engines and rocket engines. In this paper we will report our recent study on the ion chemistries of TEB relevant to the charged particle processes in plasmas involving TEB. The total cross section of electron ionization of TEB is found to have a maximum of 2.2×10^{-15} cm^2 at 75+10 eV electron energy. Product ions from the ionization include $C_2H^+_{2-5}$, BCH^+_4, $BC^+_{2,4,6}$, $BC_3H^+_{4,6}$, $BC_4H^+_{8,10}$ and $BC_6H^+_{15}$, among which $BC_6H^+_{15}$, $BC_4H^+_{10}$ and $BC_2H^+_6$ are the most abundant ions. These ions react with TEB via various mechanisms including charge-transfer, alkyde-transfer and association reaction. The common and major product ions from the ion-molecule reactions are $BC_4H^+_{10}$ and $BC_2H^+_6$, formed by simple ethide-transfer and ethide-transfer followed by dissociation (loss of C_2H_4), respectively.

LW1 7 Quasi Sturmian basis in two-electron continuum Coulomb problems LORENZO UGO ANCARANI, *Universite de Lorraine, France* A.S. ZAYTSEV, M.S. ALESHIN, S.A. ZAYTSEV, *Pacific National University, Khabarovsk, Russia* A new type of basis functions is proposed to describe a two-electron continuum which arises as a final state in electron-impact ionization and double photoionization of atomic systems. These two-particle basis functions are obtained, by analogy with the Green's function of two non-interacting hydrogenic atomic systems, as a (complex energy plane) convolution integral of two one-particle Quasi Sturmian functions [1]. We name these functions Convoluted Quasi Sturmian functions (CQS). By construction, a CQS function (unlike a simple product of two one-particle ones) behaves like a six-dimensional outgoing spherical wave when the hyperradius goes to infinity. This important property should be useful when solving three-body Coulomb scattering problems. It is the purpose of this contribution to explore the effectiveness of such CQS as a basis set.

[1]J. A. Del Punta, M. J. Ambrosio, G. Gasaneo, S. A. Zaytsev, and L. U. Ancarani, J. Math. Phys. **55**, 052101 (2014).

LW1 8 Triple Differential Cross Sections for single ionization of the Ethane molecule* ESAM ALI, *Missouri Univ of Sci & Tech* KATE NIXON, *Universidade Federal de Juiz de Fora* CHUAN-GANG NING, *Tsinghua University, Beijing, China* ANDREW MURRAY, *The University of Manchester* DON MADISON, *Missouri Univ of Sci & Tech* We report experimental and theoretical results for electron-impact (e,2e) ionization of the Ethane molecule (C2H6) in the coplanar scattering geometry for four different ejected electron energies $E_a = 5,10,15$, and 20 eV respectively, and for each ejected electron energy, the projectile scattering angle is fixed at 10°. We will show that the TDCS is very sensitive for the case of two heavy nuclei surrounded by lighter H nuclei. On the theoretical side, we have used the M3DW coupled with the Orientation Averaged Molecular Orbital (OAMO) approximation and proper average (PA) over all orientations. These approximations show good agreement with experimental data for the binary peaks. However, for the recoil peak region, experiment finds a noticeable peak while theory predicts no peak. No recoil peak suggests no (or very weak) nuclear scattering, so we have investigated the importance of nuclear scattering by moving the nuclei closer to the center of mass.

*This work is supported by the US National Science Foundation under Grant No. PHY-1068237 and XSEDE resources provided by the Texas Advanced Computing Center (Grant No. TG-MCA07S029).

LW1 9 Emission and Ionization Cross Sections for Atomic Oxygen* SWARAJ TAYAL, *Clark Atlanta University* OLEG ZATSARINNY, *Drake University* The B-spline R-matrix with pseudostates approach has been used to calculate electron collision emission and ionization cross sections for atomic oxygen in the electron energy region up to 150 eV. We included nineteen spectroscopic and 1097 pseudostates in the close-coupling expansion. These states were generated by a combination of B-spline box based multichannel close-coupling expansions and multiconfiguration Hartree-Fock method. The pseudostates cover the energy region up to 50 eV above the ionization limit. The inclusion of pseudostates leads to a better agreement with experimental emission cross sections. Our calculated ionization cross sections are also in very good agreement with available experimental data. The comparison of different scattering models and experiments provides an estimate of accuracy of our results.

*This work is supported by NASA and NSF.

LW1 10 Computational Study on Chemical Reaction Mechanisms of Octafluorocarbon Molecules* HEECHOL CHOI, MI-YOUNG SONG, JUNG-SIK YOON, *Plasma Technology Research Center, National Fusion Research Institute (NFRI)* PLASMA FUNDAMENTAL TECHNOLOGY RESEARCH TEAM Saturated or unsaturated octafluorocarbons(OFCs) have been used extensively in dry etching processes due to their relatively low global warming potential and their high CF_2 radical levels in commercial plasma treatments. Many experimental and theoretical studies of these species have been performed for useful information about physical and chemical properties of OFCs. However, direct experimental studies of these chemicals are difficult because of their high reactivity in plasma state and high-level theoretical approaches such as G3(MP2) and CCSD(T)/CBS need huge computational cost. Recently, it has been shown that the ωB97X-D/aVTZ method is strongly recommended as the best practical density functional theory(DFT) for rigorous and extensive studies of OFCs because of its high performance and reliability for van der Waals interactions. All the feasible isomerization and dissociation paths of OFCs were investigated at ωB97X-D/aVTZ and rate constants of their chemical reactions were computed by using variational transition-state theory(VTST) for a deep insight into OFCs' reaction mechanisms. Fates and roles of OFCs and their fragments in plasma phases could be clearly explained based on the obtained reaction mechanisms.

*This work was supported by R&D Program of "Plasma Convergence & Fundamental Research" through NFRI of Korea funded by the Government funds.

LW1 11 Gas Phase Dissociative Electron Attachment to Formamide Derivatives NMF and DMF* ZHOU LI, M. MICHELE DAWLEY, SYLWIA PTASINSKA, *University of Notre Dame* Fragmentation of biomolecules, such as nucleobases, induced by low energy electrons can lead to the break of DNA strands. Dissociative electron attachment (DEA), which can occur due to low energy interactions, is initiated with the formation of transient negative ions which exhibit characteristic resonant profiles in the product ion yield. The consequent fragmentation process can either be as simple as a single bond cleavage or a relatively complex process involving multiple bond rearrangements. Measurements of resonant peaks in ion yields and identification of ion products provide information of the resonant energies of the parent molecules as well as the fragmentation pathways. N-methylformamide (NMF) and dimethylformamide (DMF) are both derivatives of formamide which is the simplest structure containing the peptide bond linkage. In this work we identified anion fragments and measured resonance profiles of produced anions due to DEA to NMF and DMF. The anionic species produced from the two molecules were compared as well as the resonant positions and ion yields. Based on this comparison, the DEA process to the two molecules bears similarities such as leading to breaking of peptide bonds (C-N), as well as discrepancies such as absence of OCN^- in DEA to DMF. The selective property of H atom loss, which is reported in the DEA to formamide, is also justified in our experiment since no dehydrogenated DMF anion was detected.

*This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Basic Energy Sciences under Award Number DE-FC02-04ER15533.

LW1 12 Plasma Decay in Oxygen-Containing Mixtures Excited by High-Voltage Nanosecond Discharge EUGENY ANOKHIN, MAKSIM POPOV, *Moscow Institute of Physics and Technology* IGOR KOCHETOV, *TRINITI* ANDREY STARIKOVSKIY, *Princeton University* NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* Atoms and radicals produced in the discharge plasma possess excessive translational energy (a few electron-volts) The results of experimental and numerical study of the high-voltage nanosecond discharge afterglow in CO_2:O_2 and Ar:O_2 mixtures are presented for room gas temperature and a pressure of 10 Torr. Electron density during the plasma decay was measured with a microwave interferometer for initial electron densities in the range between 10^{12} and 10^{13} cm^{-3}. Plasma properties in the discharge afterglow were numerically simulated by solving the balance equations for charged particles and electron temperature. Calculations showed that the dominant positive ion species was O_2^+ and that the loss of electrons was controlled by dissociative and three-body recombination with these ions. An agreement between the measured and calculated values of electron density during plasma decay in air and pure oxygen was reached only under the assumption that the rate of three-body electron recombination with O_2^+ ions is much higher than the rate of thoroughly studied three-body recombination for atomic ions. Based on the analysis of the experimental data, the rate of three-body recombination with O_2^+ ions was extracted for thermal electrons and for electron temperatures up to 6000 K.

LW1 13 Modeling molecules responsible for the sidewall protection during the chemical dry etching of silicon related materials using F_2+ NO_x → F + FNO_x SATOMI TAJIMA, TOSHIO HAYASHI, *Nagoya Univ* KOJI YAMAKAWA, *Katagiri Engineering Co., Ltd.* MINORU SASAKI, *Toyota Technological Institute* KENJI ISHIKAWA, MAKOTO SEKINE, MASARU HORI, *Nagoya Univ* NAGOYA UNIV TEAM, KATAGIRI ENGINEERING CO., LTD. COLLABORATION, TOYOTA TECHNOLOGICAL INSTITUTE COLLABORATION We have been investigating the chemical dry etching of Si related materials using the reaction of F_2+ NO_x ($X = 1, 2$) → F + FNO_x. In our previous study, we found that this chemical dry etching technique generated anisotropic etching profile when the substrate temperature was maintained at <60°C. In this study, we evaluated the cause of the anisotropic etching by measuring the molecules present in the gas phase by Fourier Transform Infrared Spectroscopy (FTIR) followed by calculating the chemical bonding structure formed on the Si surface by density functional theory (DFT). First the reaction between SiF_4 and molecules generated by the reaction between F_2, NO_x, and adsorbed H_2O such as F_2, NO_x, FNO_x, H_2O, OH, and HF, measured by FTIR, were calculated by DFT to identify key molecules that can present in the gas phase. We found that the chemical reaction between SiF_4 and multiple FNO may play a key role to prevent the sidewall etching. The modeling at the surface reaction using DFT is in progress.

LW1 14 CAPACITIVELY COUPLED PLASMAS

LW1 15 Electromagnetic resonances of plasma column between two metallic plates SERGEY DVININ, *Lomonosov Moscow State University* VITALY DOVZHENKO, *Obukhov Institute of Atmospheric Physics RAS* OLEG SINKEVICH, *National Research University Moscow Power Engineering Institute* It is known that there are two types of electrodynamic resonances of bounded supercritical plasma, placed between the two metal planes are possible. The first type is associated with the excitation of surface waves propagating along the lateral surface [1]. The second one is caused by standing surface waves in the sheath at plasma-metal boundary [2 – 4]. This work is concerned with theoretical study of the resonance properties of plasma slab in cases where both effects can be observed together. Resonance densities and frequencies are calculated. Solution of Maxwell's equations is demonstrated that directions of energy flows in first and second cases are opposite. Energy transfer to lateral surface waves is prevailing, if the field frequency is higher than the frequency, corresponding to the geometric plasma-sheath resonance [5]. Amplitude of waves at plasma metal boundary becomes greater in opposite case. Discharge properties in both cases are calculated including joint excitation.

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LW1 16 Filamentation of capacitive Radio-Frequency discharge at low pressures SERGEY DVININ, *Lomonosov Moscow State University* ZAFARI KODIRZODA, *Tajik National University, Faculty of Physics* It is known that ionization instability may occur in high-frequency (HF) discharges, resulting in breaking of uniform plasma density distribution [1 – 3]. The model [1] dealt with an instability associated with the peculiarities of transfer processes and electron kinetics for non-Maxwellian electron energy distribution function. We consider the stability of capacitive discharge between two cylindrical electrodes with radii R and r at low pressures. It is shown that for large electrodes R–r ≪ r the uniform density distribution in the discharge can be unstable. Instability occurs if the frequency of supporting field is higher than geometric plasma-sheath resonance [4] frequency, and the output impedance of the RF generator is large enough. Instability is connected with falling current-voltage characteristics and leads to discharge filamentation. Analytical model, based on equations for filament boundary motion, is developed. The model allows to determine the size of discharge chamber area occupied by plasma, the density of electrons, and current-voltage characteristics. Numerical calculations confirm analytical results.

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LW1 17 Electron heating via the self excited plasma series resonance in multi-frequency capacitive plasmas STEVEN BRANDT, EDMUND SCHUENGEL, *West Virginia University* ZOLTAN DONKO, IHOR KOROLOV, ARANKA DERZSI, *Hungarian Academy of Sciences* JULIAN SCHULZE, *West Virginia University* In a combined approach of PIC/MCC simulations and a theoretical model based on an equivalent circuit, the self-excitation of Plasma Series Resonance (PSR) oscillations and their effect on the electron heating in geometrically symmetric capacitively coupled radio frequency (CCRF) plasmas driven by multiple consecutive harmonics of 13.56 MHz is investigated. The discharge symmetry is controlled via the Electrical Asymmetry Effect, i.e. by varying the total number of harmonics and tuning the phase shifts between them. It is demonstrated that PSR oscillations of the electron current density will be self-excited, if (i) the charge-voltage relation of the plasma sheaths deviates from a simple quadratic behavior and if (ii) the inductance of the plasma bulk exhibits a temporal modulation. Both effects are neglected in existing models of the PSR, but found to be crucial here. The effect of the PSR self-excitation on other plasma parameters, such as the potential profile, is illustrated by applying Fourier analysis. High frequency oscillations in the entire spectrum between the applied frequencies and the local electron plasma frequency are observed. The electron heating is demonstrated to be strongly enhanced by the PSR and complex electron heating dynamics are observed.

LW1 18 Resonance Phenomena of Voltage and Current Driven Capacitively Coupled Plasmas SEBASTIAN WILCZEK, JAN TRIESCHMANN, *Ruhr-University Bochum, Germany* JULIAN SCHULZE, EDMUND SCHUENGEL, *West Virginia University, Morgantown, USA* RALF PETER BRINKMANN, *Ruhr-University*

Bochum, Germany ARANKA DERZSI, IHOR KOROLOV, ZOLTÁN DONKÓ, *Wigner Research Centre for Physics, Budapest, Hungary* THOMAS MUSSENBROCK, *Ruhr-University Bochum, Germany* The plasma series resonance is a fundamental phenomenon due to the nonlinear interaction between the plasma bulk and the sheaths of a capacitive discharge. It has been proven to play an important role in the context of electron heating. Furthermore, recent results indicate that the manifestation of harmonics in the plasma current due to the plasma series resonance is responsible for a nonlinear standing wave effect and, consequently, spatial inhomogeneities in the power deposition. It is important to note that the plasma series resonance is a current governed resonance and that it can only be excited in voltage driven systems. Particle-In-Cell simulations however show that also in current driven systems resonances can occur due to the non-linear excitation of harmonics in the conduction and displacement current. In this work, the differences between voltage and current driven capacitive discharges in terms of their nonlinear behavior are investigated. It is found that under certain conditions nonlinear plasma parallel resonances are excited which are able to support the electron heating.

LW1 19 Atmospheric Pressure RF Discharge for Nanocrystal Synthesis* NARULA BILIK, BENJAMIN GREENBERG, UWE KORTSHAGEN, *Univ of Minn - Minneapolis* Atmospheric pressure plasmas are inexpensive alternatives to low-pressure plasmas. Constructing such plasmas is a challenge due to the instabilities associated with high pressure. Most RF atmospheric pressure plasmas are microplasmas built to preserve the Paschen's law scaling, leading to small volumes and low production quantity. Here we present a large-volume (non-micro scale) atmospheric pressure plasma for nanocrystal synthesis. The plasma is a dielectric barrier discharge with an average gap spacing of 2.4 mm. The discharge appears uniform viewed by the eye. The gap spacing is non-uniform: discharge is first initiated in a region where the gap spacing is minimum to encourage the formation of free electrons and metastables, then the discharge expands to fill the entire volume as the voltage is increased; this way, the discharge remains uniform over large volume. Zinc oxide nanocrystals with a crystallite size of about 12 nm were produced in the reactor. The shape of the nanoparticles sensitively depends on the residence time. Near-circular particles were produced when using a carrier flow rate of 5 slm, while elongated particles were produced when using a carrier flow rate of 10 slm.

*This work was supported by the DOE Plasma Science Center for Predictive Control of Plasma Kinetics.

LW1 20 Fluid simulation and experimental measurement of radical densities in capacitively coupled CF_4/Ar plasma* YING-SHUANG LIANG, YONG-XIN LIU, YU-RU ZHANG, WEN-YAO LIU, YOU-NIAN WANG, *Dalian University of Technology* Both of the two-dimensional self-consistent fluid model and the experimental diagnostic method are employed to investigate the effects of the external parameters on the plasma parameters, especially on the production and loss of the CF_2 and F radicals, in the capacitively coupled CF_4/Ar plasmas driven at 60 MHz. It is observed that the CF_3 and F are the two main radicals under all the investigated conditions. With the increase of the discharge power, the densities of the CF_2 and F radicals increase almost linearly. By comparing the calculated and experimental results, it is found that the main production mechanism of the CF_2 radical is the electron-impact dissociation of CF_4. However, the electron-impact dissociation of CF_3 plays an important role in the production of the F radicals, besides the electron-impact dissociation of CF_4. The general qualitative agreement between the calculated and the experimental results indicates that the present fluid model correctly describes the CF_4/Ar capacitive discharge.

*This work was supported by the National Natural Science Foundation of China (NSFC) (Grant Nos. 11335004, 11405018, 11405019) and the Important National Science and Technology Specific Project (Grant No. 2011ZX02403-001).

LW1 21 Spatial Distribution of Plasma Parameters in an Asymmetric Coaxial Discharge JEREMY PESHL, JANARDAN UPADHYAY, *Old Dominion University* MILKA NIKOLIC, *James Madison University* ALEXANDER GODUNOV, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Old Dominion University* Plasma processing of superconductive radio-frequency (SRF) cavities provides the unique opportunity of tailoring the inner surfaces for better SRF properties in addition to being a less expensive and more environmentally friendly method of processing the cavities. An asymmetric coaxial capacitively coupled RF discharge is a natural approach to plasma processing of an SRF cavity. Although the experimental setup and process parameters necessary to generate the reversal of the asymmetry and achieve the 3D surface processing have been established [1], information about the plasma properties such as electron temperature, ion energy, and plasma density remain elusive for asymmetric coaxial capacitively coupled plasmas (CCP). For diagnostic purposes, an RF (15.36 MHz) coaxial CCP is made using a 12″ long and 2″ diameter powered inner electrode and a 12″ long 3.85″ inner diameter outer grounded electrode. Plasma parameters are measured using external and internal optical emission spectrometers and a Langmuir probe. Spatial distributions of plasma parameters are collected by changing the radial positions of the measurement devices. Comparative analysis of the data from each diagnostic tool is conducted to ensure consistency of the quantitative results.

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LW1 22 Structure of Velocity Distribution of Sheath-Accelerated Secondary Electrons in Asymmetric RF-DC Discharge ALEXANDER V. KHRABROV, JOHAN CARLSSON, IGOR D. KAGANOVICH, *Princeton University* PETER L. VENTZEK, LEE CHEN, *Tokyo Elecron America* Low-pressure capacitively-coupled discharges with additional DC bias applied to a separate electrode find important industrial applications. Prime examples are plasma-assisted etching and deposition technologies. An interesting and important property of such discharges, observed in experiments, is an enhanced and non-monotonic high-energy tail of the electron velocity distribution function (EVDF) near the surface of the RF (a.k.a. powered) electrode. Such structures, at energies of several hundred eV, are possibly caused by secondary electrons emitted from the electrodes and interacting with two high-voltage sheaths; a stationary sheath at the DC electrode and an oscillating, self-biased sheath at the powered electrode. We have performed particle simulations where the features in the EVDF of electrons impacting the RF electrode are fully resolved at all energies. An analytic model has been developed to predict existence of peaked and step-like structures in the EVDF. The latter electrons can be grouped by the number of bounces between the sheaths during their lifetime in the discharge. Each of the groups may give rise to an individual peak in the distribution. Initial particle-in-cell simulations of these effects will be reported.

LW1 23 Particle-in-cell simulations of a large capacitively coupled plasma discharge* DENIS EREMIN, DANIEL SZEREMLEY, THOMAS MUSSENBROCK, RALF-PETER

BRINKMANN, *Ruhr-University Bochum* A capacitively coupled low-pressure plasma discharge with large electrode radius (25 cm) and a large grounded side chamber radius (25 cm) is simulated with a particle-in-cell code for different driving frequencies. The simulations reveal the importance of plasma dynamics in the side chamber for the whole plasma discharge. In particular, it is observed that at 60 MHz the plasma density profile in the side chamber features an unexpected hump close to the side chamber entrance. At the same time the self-bias at this frequency virtually vanishes despite large geometrical asymmetry of the reactor, which is also not anticipated in a single-frequency driven discharge. The plasma density profile uniformity exhibits a pronounced frequency dependence as well.

*The authors gratefully acknowledges support by DFG (German Research Foundation) within the framework of Research Unit SFB TR-87.

LW1 24 Modeling of dual frequency capacitive discharges with pulse-modulated power input SCHABNAM NAGGARY, EFE KEMANECI, RALF PETER BRINKMANN, *Ruhr-University Bochum* MOHAMMED SHIHAB, *Tanta University Egypt and Univerity of Rostock* ZOLTÁN KOVÁCS, MUSTAFA MEGAHED, *ESI Group* Pulse-modulated capacitive discharges provide additional degrees of freedom to modify the characteristic features of plasma constituents and control the ion energy distribution function (IEDF). In addition, dual frequency capacitive discharges enable a functional separation of the sheath voltages and the plasma composition, allowing for a more precise control of the ion energy distribution [1]. In this contribution, a dual frequency pulse-modulated capacitive discharge is numerically studied. In the first part of the investigation, a global model is used to provide a quick assessment of the discharge characteristics. The model consists of two parts, a multimode lumped circuit model and a chemical global model. With an iterative coupling of the two models, the plasma parameters are obtained self-consistently. An analytic sheath model then delivers the IEDF [2,3]. Multiple scenarios are parametrically investigated. Furthermore, a spatially resolved analysis is conducted using the multiphysics tool CFD-ACE+. This is compared with the global modeling approach particularly concerning the key factors accuracy and computational cost.

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LW1 25 Capacitively coupled dc/rf discharges driven by arbitrary linear circuits JOHN CARY, *University of Colorado and Tech-X Corporation* MING-CHIEH LIN, *Department of Electrical and Biomedical Engineering, Hanyang University, Seoul 133-791, South Korea* DAVID SMITHE, SEAN ZHOU, *Tech-X Corporation* We have developed a method for computing the system of an arbitrary linear circuit coupled to a capacitively coupled plasma discharge. The method relies on the known method of separation of the vacuum and plasma generated fields for the discharge. It is time centered and implicit in the circuit quantities, thus guaranteeing second-order accuracy in time. This method has been implemented in the VSim engine (Vorpal). Numerical verification of the order of accuracy will be shown.

LW1 26 Experimental study of a very high frequency (162MHz) capacitively coupled multi-tile electrode plasma source NISHANT SIRSE, BERT ELLINGBOE, *Dublin City University, Ireland* In the recent years, plasma discharges excited at very high frequency (30-500MHz) has attracted much attention due to its ability to perform etching and deposition of large area substrates. VHF discharges yield high plasma density and low electron temperature and enable enhanced plasma dissociation. However, the plasma chemistry and power coupling mechanism in VHF discharges is not fully understood. In this article, we present an experimental study on nitrogen plasma produced by a VHF (162 MHz) multi-tile electrode. Electron density profile and gas temperature (rotational and vibrational) are measured as a function of rf power (100-1500W) and gas pressure (50mTorr-1Torr). Tile centre and Tile edge data are presented to realize the power coupling mechanism at different position in the multi-tile electrode discharge. It is observed that the plasma density increases monotonically with a rise in VHF power level at both positions while decreasing with an increase in the operating gas pressure. At a low gas pressure (50mTorr), plasma density profile shows a maximum at the tile centre and minimum at the tile edge position, whereas, at high gas pressures (500mTorr – 1 Torr) edge effects are observed. Measured rotational temperature ($\sim$ 350-450 K) is slightly above room temperature. Vibrational temperature, measured from 6500-8000 K, is increasing initially with a rise in rf power ($<$1 kW) and then saturates (above 1 kW). Similar to the plasma density profile, high vibrational temperature is measured at the tile edge compared to the tile centre.

LW1 27 Two-dimensional Simulations of a VHF H_2 Plasma for Different Discharge Gaps KUAN-CHEN CHEN, KUO-FENG CHIU, *Department of Materials Science & Engineering, Feng-Chia University, Taichung, 40724, Taiwan* KOHEI OGIWARA, LI-WEN SU, KIICHIRO UCHINO, YOSHINOBU KAWAI, *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan* A capacitively coupled plasma (CCP) is widely used for plasma applications. Since a tandem silicon thin film solar cells using a VHF plasma source was proposed, a study of a VHF plasma has been popular in solar cell fields. In addition, a high speed deposition of microcrystalline silicon has been achieved by a high pressure depletion method. In plasma etching, a two frequency CCP has been operated at relatively high pressures. Thus, it is important to examine the characteristics of a capacitively coupled VHF plasma at high pressures. However, a spatial distribution of the plasma parameters at a narrow gap has not been measured because of the measurement difficulty. Thus, we examined an axial distribution of the plasma parameters for different discharge gaps by the simulation using Plasma Hybrid Module. A VHF voltage (frequency: 60 MHz) was applied on parallel plate electrodes The discharge gap was varied from 8 mm to 20 mm. The electron temperature around the electrode was higher than that at the center. When the applied voltage was increased, the electron density increased while the electron temperature decreased near the center. The gap dependence of the plasma parameters was also studied.

LW1 28 INDUCTIVELY COUPLED PLASMAS

LW1 29 Fluid simulation of feedstock gas transporting properties in argon inductively coupled plasmas SHU-XIA ZHAO, CHENG CHEN, ZHAO FENG, YOU-NIAN WANG, *Dalian University of Technology* PSEG TEAM* The flow properties of feedstock gas in an argon inductively coupled plasma are investigated by compressible Navior-Stocks equation. The inlet gas flow rate and outlet fixed pressure are adjusted in their respective parameter ranges, 50-1000sccm and 20-1000mTorr. The axial symmetry and no-slip wall boundary condition are applied at the reactor axis and walls, respectively. Multi reactor configurations are derived from the realistic industry application. The results show that the gas flow velocity almost linearly increases with gas flow rate since high flow rate can result in high inlet gas velocity. The gas velocity still decreases at high outlet pressure due to the fact that the density is high at high pressure and hence the velocity drops at constant inlet mass flux density. At all considered cases, the gas is compressible, especially at the sidewall, as the gas flow rate is high and pressure is low enough. Last, the aspect ratio of reactor has significant influence on both the magnitude and profile of gas velocity.

*Plasma Simulation and Experiment Group.

LW1 30 Chemically active species in an Oxygen Inductively Coupled Plasma* NATHANIEL LY, JOHN BOFFARD, CHUN LIN, AMY WENDT, *University of Wisconsin-Madison* SVETLANA RADOVANOV, HAROLD PERSING, ALEXANDRE LIKHANSKII, *Applied Materials, Varian Semiconductor* Oxygen plasmas are used in a wide variety of applications including ion implantation and photoresist striping. Here we combine noninvasive optical emission spectroscopy (OES) measurements and numerical simulations to investigate the plasma parameters in both oxygen inductively coupled plasmas (ICP) and oxygen-argon ICPs. An emission model makes use of available electron impact excitation cross sections for atomic and molecular oxygen to relate measured O and O_2^+ emission intensities to corresponding plasma parameters, including the electron temperature, electron density, and the dissociation fraction of the neutral oxygen. For plasma simulations we use the CRTRS, 2D/3D code that selfconsistently solves for ICP power deposition, electrostatic potential and plasma dynamics in the driftdiffusion approximation (or full momentum equations). Comparison of the experimental OES measurements are used to check the validity of the plasma simulation which yields results that the OES approach has difficulty in measuring including the relative fluxes of O^+ and O_2^+, which is important for ion implantation.

*The authors acknowledge support from NSF Grant PHY-1068670, and from Dr. Shahid Rauf for developing CRTRS.

LW1 31 Characterization of radical production mechanism in CHF_3 and CF_4 inductively coupled plasmas YAPING WANG, SHUXIA ZHAO, *Dalian University of Technology* PSEG TEAM Inductively coupled fluorocarbon (fc) plasmas are widely used in Si/SiO_2 etching industry as they provide active radicals which are reactive to the Si or SiO_2 materials. It is well known that CHF_3 plasma has relatively low density ratio of F vs. CF_x radicals and hence high etching selectivity, as compared with the CF_4, due to the fact that one F is replaced by H in CHF_3 molecules and H can abstract F from fluorocarbon radicals to form HF. However, for now, much elaborate details are still missed in the literature. Therefore in this work, a fluid model is used to characterize the radical production components in these two different fc plasmas. The fluid model includes continuity and energy equations for electrons, continuity and momentum equations for ions and continuity equations for radicals. An electromagnetic model is used to calculate the electric field which is generate by coupling coil current and Poisson equation is used to calculate the static field within the plasma. The model predicts the electron density, ion density and radical density of CHF_3 plasma. For now the simulations of CF_4 plasma are still under construction. We expect to compare the different radical production mechanisms in the CHF_3 and CF_4 plasma sources in new future.

LW1 32 Electron heating and electronegativity during E-H transition in inductively coupled RF oxygen discharge* THOMAS WEGNER, CHRISTIAN KÜLLIG, JÜRGEN MEICHSNER, *University of Greifswald* The E-H transition of a planar inductively coupled RF oxygen discharge was investigated using the phase resolved optical emission spectroscopy. Beside of experimental methods, an analytical calculation of the negative ion density using a particle balance equation reveals an information about the electronegativity, too. The E-mode at low RF power is characterized by RF sheath heating during the sheath expansion and the electrical field reversal which appears during the sheath collapse. The last one is a sign for high electronegativity. The axial distance of the maximum excitation rate increases due to the increasing sheath thickness. The E-H transition in this exemplary discharge is continuously and the electron heating changes smoothly. During the transition into the H-mode the capacitive and inductive heating are present and a hybrid mode is observed. Further, the electronegativity is reduced. As a result of the shrinking sheath thickness and skin depth, the axial distance of the maximum excitation rate decreases drastically. In the pure H-mode two separated patterns appear representing the electron heating for each half cycle. Due to the increases of the electron density, the skin depth drops and leads to a further decrease of the axial distance of the maximum excitation rate.

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LW1 33 Experimental investigation on collisionless electron heating mechanism through electron energy probability function measurement in a low pressure inductively coupled plasma HYUN-JU KANG, *Department of Electrical Engineering, Hanyang University* DEUK-CHUL KWON, *National Fusion Research Institute* CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Electron energy probability functions (EEPFs) were measured at various powers and frequencies in low pressure inductively coupled plasma. It is found that the EEPFs becomes flatten and the plateau region is shifted to lower energy, as driving frequency decreases or input power increases. The EEPFs with plateau energy region indicates that there is a powerful electron heating mechanism in semi-infinite discharge condition. This experimental result will be also compared to the simulation results including bounce resonance and transit time resonance heating.

LW1 34 Spatial distribution of floating potential at wafer level in inductively coupled plasmas AIXIAN ZHANG, JI-HWAN PARK, JIN-YONG KIM, YU-SIN KIM, CHIN-WOOK CHUNG, *Hanyang Universiy* Spatial distribution of floating potential was measured by using a wafer-type probe array. At low gas pressure, the floating potential distribution has a parabolic shape with a maximum value at the center, regardless of discharge condition. However, the floating potential distribution was remarkably changed, as the gas pressure increases in an electronegative plasma. These results are because the gas pressure changes the discharge property from nonlocal to local kinetics. Besides, negative ions can change the floating potential distribution. This study will be helpful to understand charging damage in metal oxide semiconductor manufacturing process.

LW1 35 Electron heating and control of electron energy distribution in hybrid plasma source for the enhancement of the plasma ashing processing HYO-CHANG LEE, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* In this study, control of the electron energy distribution function (EEDF) is investigated in hybrid plasma source with inductive and capacitive fields. With the addition of a small amount of antenna coil power to the capacitive discharge, low energy electrons are effectively heated and the EEDF is controlled. This method is applied to the ashing process of the photoresistor (PR). It is revealed that the ashing rate of the PR is significantly increased due to O radicals produced by the controlled EEDF, even though the ion density/energy flux is not increased. The roles of the power transfer mode, the electron heating, and the discharge parameters are also presented in the hybrid plasma source. This work can be used to an inter-ashing method during etching process.

LW1 36 Experimental investigation on collisionless heating in a finite size inductively coupled plasma SEULI GU, *Department of Nanoscale Semiconductor Engineering, Hanyang University* HYUN-JU KANG, YU-SIN KIM, YOON-MIN CHANG, *Department of Electrical Engineering, Hanyang University* DEUK-CHUL KWON, *Plasma Technology Research Center, National Fusion Research Institute* CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* The electron energy probability functions (EEPFs) were measured in low pressure and planar-type inductively coupled plasma at various chamber heights. The plateau on the EEPFs was observed and the corresponding energy region was shifted to higher energy region with increasing chamber height. Since the electron mean free path is larger than the discharge gap length, the plateau shifting could be understood by an effect of collisionless electron heating. From calculated energy diffusion coefficient, a possible heating mechanism is the electron bounce resonance.

LW1 37 Collisionless electron heating in periodic arrays of inductively coupled plasmas UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum* KHRISTO TARNEV, *Department of Applied Physics, Technical University-Sofia* A novel mechanism of collisionless heating in large planar arrays of small inductive coils operated at radio frequencies is proposed [1]. A periodic array of multiple coils provides a well-structured, dynamic electric field which allows resonant electrons moving in the plane to gain high energies. Two types of tailored periodic structures are studied. In the ortho-array currents in all coils are in phase while in the para-array currents in adjacent coils are 180° out of phase. The concept is investigated analytically by solving the Vlasov equation and by a single particle simulation combined with Monte Carlo collisions with Argon atoms. Scaling parameters, resonances, energy exchange, and distribution functions are obtained. Analytical and numerical results are in good agreement. Pressure and electric field dependences are studied. Stochastic heating is found to be most efficient when the electron mean free path exceeds the size of a single coil cell. Then the mean energy increases approximately exponentially with the electric field amplitude.

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LW1 38 Decomposition of carbon dioxide using inductively coupled plasma KYUNG-HYUN KIM, KWAN-YONG KIM, HYO-CHANG LEE, CHIN-WOOK CHUNG, *Hanyang Univ* Decomposition of carbon dioxide is studied in Ar/CO_2 mixture inductively coupled plasmas (ICP). To measure decomposition rate of CO_2, optical emission actinometry is used. When the ICP power or mixing ratio is changed, the decomposition rate is evolved depending on the discharge mode. This result is deeply analyzed with both the measurement of the plasma parameters, such as plasma density, electron temperature, and electron energy distribution and the calculation of rate constants for the CO_2 plasma.

LW1 39 Properties of large area weakly magnetized inductively coupled plasma measured by cutoff probe and tuned single Langmuir probe EUI-JEONG SON, YONG-SOO YOUN, DONG-HYUN KIM, HAE JUNE LEE, HO-JUN LEE, *Pusan National University* Applicability of cutoff probe in weakly magnetized plasmas was investigated using Drude model and electromagnetic field simulation. It was shown that the cutoff probe method can safely be used for weakly magnetized high density plasma sources. Cutoff probe system with two port network analyzer has been prepared and applied to measure electron density distributions in large area, 13.56 MHz driven weakly magnetized inductively coupled plasma source. The results shown that, by applying uniform magnetic field of 12 Gauss to 5 mTorr Ar plasma, peak electron density is increased by a factor of 3 compared with non-magnetized plasma. However, radial density profile becomes more center-high and non-uniform. As the rf power increases the radial uniformity is improved. Electron temperature decreases at the chamber center and increases at the edge when the plasma is magnetized. Resulting radial temperature distribution becomes U-shape. These electron temperature profiles are well agree with self-consistent fluid simulation results. On the other hand, simulation predicted that the radial electron density distribution has M-shape, which is not agreed with experimental results. The origin of the discrepancy between simulation and experimental results are not clear.

LW1 40 MAGNETICALLY -ENHANCED PLASMAS: ECR, HELICON, MAGNETRON, OTHERS

LW1 41 Low-voltage operating mode of a high-current magnetized cold-cathode plasma* TIMOTHY SOMMERER, STEVEN ACETO, DAVID SMITH, *General Electric Research* NICHOLAS HITCHON, JAMES LAWLER, *University of Wisconsin* A series of approximations and simple models is used to estimate the properties of a cold-cathode plasma in a high-voltage, high-power gas switch for use in grid-scale electric power conversion. The active plasma volume is a plane-parallel gap $\approx$1 cm filled with helium at a pressure on order 0.1 torr. A magnetic field in the region adjacent to the cathode is used to increase the current density to practical levels >1 A/cm^2. The plasma can operate in a "low voltage mode" ($\approx$80 V) that has the appearance of a constricted attachment at the cathode surface and a more diffuse region toward the anode. Cathode material is absent from the plasma emission spectrum. Various attempts to model the spot indicate that the plasma in the constriction is near full ionization, and that there is a dynamic balance of neutral gas atoms between the constriction, the cathode surface, and the neighboring diffuse plasma. The electron emission mechanism is assumed to be conventional, by ion impact, but field emission may contribute.

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LW1 42 Non-diffusive perpendicular transport of strongly magnetized plasma MIN-KEUN BAE, *Hanyang University* RICHARD PITTS, *ITER Organization* JUN GYO BAK, SUK-HO HONG, HEONG SU KIM, *NFRI* KYU-SUN CHUNG, *Hanyang University* Characteristics of high energy particles spilled out from magnetically confined plasma reaching the wall are measured by electric probes. Energetic plasma bursts, called filament, during the edge localized mode(ELM) of fusion device are non-diffusively moving to the wall, which is perpendicular to the magnetic field ($B_t = 1 \sim 3$ T). These intermittent ELM filaments can carry significant particle and heat to the first wall. Poloidal probes which are composed of two triple probes (TPs) and one Mach probe(MP) installed at first wall of Korea Superconducting Tokamak Advanced Research(KSTAR) device. These probes are located 2398 mm from the machine center and 74 mm behind the poloidal limiter. Poloidal probes are used as a triple probe and measured ion saturation current and floating potential with 200 kHz. From the direct measurement of electron temperature, ion saturation currents (TP) and Mach numbers (MP), relevant plasma parameters such as heat flux, three dimensional flow velocities, and plasma density have been deduced.

LW1 43 Origin of Substrate Heating During Oxide Film Deposition by DC Magnetron Discharge and Superposition of VHF Power KENTA SETAKA, TAKASHI FUKUI, KENSUKE SASAI, *Nagoya University* HIROTAKA TOYODA, *Nagoya University, PLANT, Nagoya University* Magnetron plasmas are one of the important tools for thin film deposition such as metal, oxides and so on. In general, quality of sputter deposited film is influenced by substrate temperatures and this implies that the discharge condition is strongly related to the film quality. In this study, substrate temperature is measured in a DC magnetron plasma with VHF power superposition and origin of substrate heating is investigated. In the experiment, ITO films are deposited by a DC magnetron sputter source to which VHF power is superposed. Substrate temperature is measured as a function of VHF power fraction with respect to total discharge power, i.e., DC and VHF powers. The substrate temperature shows the minimum at VHF power fraction of $\sim 60\%$. From Langmuir probe measurement and laser absorption spectroscopy, both plasma density and gas temperature monotonically increases with the VHF fraction, which explains the substrate temperature increase at high VHF power fractions. However, the temperature increase at low VHF power fraction cannot be explained by heat flux by ions or discharge gas. Contribution of negative ion impingement to the substrate is considered to be the origin of the substrate temperature at low VHF power fractions or conventional DC sputter depositions.

LW1 44 Production of fast plasma flows with a steady state high density plasma in TPD-Sheet IV TAKAAKI IIJIMA, YUTA TANAKA, TAKUYA HASE, TOSHIKIO TAKIMOTO, AKIRA TONEGAWA, *Tokai University* KOHNOSUKE SATO, *Chubu Electric Power Co. Inc.* KAZUTAKA KAWAMURA, *Tokai University* Ion acceleration of high density sheet plasma (ca.10^{18}m^{-3}) in a non-uniform magnetic field by ion-cyclotron resonance (ICR) is investigated in a linear plasma device, TPD-Sheet IV. The radio frequency (RF) electrodes consist of two parallel plates. The ion energy along the axis of the magnetic field or in the perpendicular direction was measured using a Faraday cup. The experiment was conducted using helium gas and a discharge current of 50 A. The ion energy in the direction perpendicular to the magnetic field line increases by ion-cyclotron resonance. Ions are also accelerated along the axis of the magnetic field line due to the magnetic field gradient along the axis.

LW1 45 Modeling of the Reactive High Power Impulse Magnetron Sputtering (HiPIMS) process JON TOMAS GUDMUNDSSON, *University of Iceland* DANIEL LUNDIN, *Université Paris-Sud* MICHAEL RAADU, NILS BRENNING, *KTH Royal Institute of Technology* TIBERIU MINEA, *Université Paris-Sud* Reactive high power impulse magnetron sputtering (HiPIMS) [1] provides both a high ionization fraction of the sputtered material and a high dissociation fraction of the molecular gas. We demonstrate this through an ionization region model (IRM) [2] of the reactive Ar/O_2 HiPIMS discharge with a titanium target. We explore the influence of oxygen dilution on the discharge properties such as electron density, the ionization fraction of the sputtered vapor and the oxygen dissociation fraction. We discuss the important processes and challenges for more detailed modeling of the reactive HiPIMS discharge. Furthermore, we discuss experimental observations during reactive high power impulse magnetron sputtering sputtering (HiPIMS) of Ti target in Ar/N_2 and Ar/O_2 atmosphere. The discharge current waveform is highly dependent on the reactive gas flow rate, pulse repetition frequency and discharge voltage. The discharge current increases with decreasing repetition frequency and increasing flowrate of the reactive gas [3].

[1]J. T. Gudmundsson *et al.*, J. Vac. Sci. Technol. A **30**, 030801 (2012).

[2]M. A. Raadu *et al.*, Plasma Sources Sci. Technol. **20**, 065007 (2011).

[3]F. Magnus *et al.*, J. Vac. Sci. Technol. **30**, 050601 (2012).

LW1 46 Measurements of steady-state radial cross-field ion flows in a helicon plasma DEREK THOMPSON, EARL SCIME, M. UMAIR SIDDIQUI, *West Virginia University* Radial ion drift velocity, electron temperature, plasma potential, and density profiles in front of a grounded boundary plate were obtained in a helicon plasma for ρ_i/λ ranging from 0.34 to 1.6, in order to directly investigate the effects of ion-neutral collisions on cross field transport. Measurements indicate that such simple scalings do not rigorously predict the behavior of cross-field drift profiles in the presence of simple complications such as multi-dimensional flows. Results are compared to basic fluid models in order to gain further insight on possible complications affecting cross-field transport.

LW1 47 HIGH PRESSURE DISCHARGES: DIELECTRIC BARRIER, DISCHARGES, CORONAS, BREAKDOWN, SPARKS

LW1 48 The breakdown process in an atmospheric pressure nanosecond parallel-plate discharge YI-KANG PU, BANG-DOU HUANG, *Tsinghua Univ* KEISUKE TAKASHIMA, *Tohoku University* XI-MING ZHU, *Ruhr-University Bochum* The breakdown process in an atmospheric pressure nanosecond discharge with parallel-plate electrodes is investigated by temporally and spatially resolved optical emission spectroscopy (OES). The electric field is obtained from the Stark splitting of the He I 492.1 nm line. From the line ratio and a collisional-radiative model, the Te, high and Te, low (representing the effective Te in the high energy and low energy part of the EEDF, respectively) are obtained. It is found that during the breakdown process the electric field is enhanced at the ionization wave front, while it is weakened behind the wave front. This spatial profile of the electric field strongly correlates with that of both the Te, high and Te, low. The Te, high is much larger than the Te, low, which indicates that an elevated high energy tail in the EEDF is being built up under the strong electric field during the breakdown process. This argument is supported by the result from a Monte-Carlo simulation.

LW1 49 ROS/RNS Production in Water Using Various Discharge Plasma KAZUHIRO TAKAHASHI, KOHKI SATOH, HIDENORI ITOH, HIDEKI KAWAGUCHI, *Muroran Institute of*

Technology IGOR TIMOSHKIN, MARTIN GIVEN, SCOTT MACGREGOR, *University of Strathclyde* A pulsed discharge, a DC corona discharge and an atmospheric pressure plasma jet are generated above water, the off-gas of a packed-bed dielectric barrier discharge (PB-DBD) is sparged into water, and then reactive oxygen species and reactive nitrogen species in the water are investigated. H_2O_2, NO_3^- and a trace of NO_2^- are produced in the water after the plasma exposure. H_2O_2 concentration decreases when NO_3^- concentration increases, so that this is likely that OH radical to produce H_2O_2 by $OH + OH \rightarrow H_2O_2$ is consumed in the NO_3^- production by $NO_2 + OH \rightarrow HNO_3 \rightarrow NO_3^- + H^+$ (in water). Since no species is detected in water by the sparging of the PB-DBD off-gas containing more than 1000 ppm of O_3, O_3 does not contribute to produce H_2O_2 in water. Further, only NO_3^- is produced by the sparging of the off-gas containing N_2O_5 and HNO_3. This leads that H_2O_2 and NO_2^- can be produced by short-lifetime species in plasma. In this work, the highest generation efficiency of H_2O_2 and NO_2^- are respectively 3,820 μg/Wh and 830 μg/Wh by the pulsed-plasma exposure, and that of NO_3^- is 2,530 μg/Wh by the off-gas sparging of the PB-DBD.

LW1 50 Numerical Study of Breakdown Pattern Induced by Intense Microwave under Atmospheric Conditions* MASAYUKI TAKAHASHI, OHNISHI NAOFUMI, *Tohoku Univ* Breakdown experiment using intense microwaves was conducted under atmospheric pressure, and plasma arrays were observed in nitrogen. However, in helium breakdown, the breakdown pattern is different from that of nitrogen. Discrete plasma pattern was obtained in the downstream region of the plasma propagation. On the other hand, the upstream region shows a diffusive plasma pattern in the helium breakdown. Propagation speed of the plasma front has dependencies on chemical species; however, organized discussion of the breakdown process was not conducted for several chemical species. We simulate the microwave discharge process for nitrogen, helium, and hydrogen using a one-dimensional fluid modeling to examine dependencies of the breakdown structure on chemical species. Plasma arrays are obtained in nitrogen and hydrogen because the electron diffusion is smaller than that of helium. On the other hand, the diffusive pattern is reproduced in helium because the electron diffusion is larger. The propagation speed of the helium breakdown is larger than that of nitrogen and hydrogen because of larger diffusion and larger ionization. We will discuss that dependencies of the breakdown process on chemical species based on a multi-dimensional fluid model in the full paper.

*This work was supported by JSPS KAKENHI Grant Number H255089.

LW1 51 Chemical Kinetics Reduction of High Pressure Non-Equilibrium Plasma Discharges in Complex Gases Using Principal Component Analysis ASHISH SHARMA, LAXMINARAYAN L. RAJA, *The University of Texas at Austin* Kinetic models of plasma discharge in complex gases involve solving the continuity equation for each reaction for updation of species at each time step. The number of reactions, especially in complex gases like methane, can be really large and thus, this approach is computationally expensive. It also makes the system very stiff due to orders of magnitude difference in rate constants. Principal Component Analysis (PCA) is technique which allows the identification of significant variables governing the course of a chemical kinetics model. This allows us to describe its behavior in a lower dimensional space with lesser variables and reduction is obtained since kinetic reactions only need to be solved for these principal components and not for all the species in the plasma discharge model. The non-linear nature of the source terms in plasma discharges also makes the traditional PCA technique less effective. In the current work an attempt has been made to develop an approach for reduction of chemical kinetics of non-equilibrium plasma discharges in methane gas at atmospheric pressure using PCA. The approach also explores the use of linear and non-linear source term reconstruction techniques for effective projection of source terms back to the higher dimensional space.

LW1 52 Timing Control of Self-organized Dielectric Barrier Discharge and Influence of Discharge Driving Frequency* JUNICHI SUGAWARA, *Iwate University* YUKI KUBOTA, *None* HIDENORI OKI, SEIJI MUKAIGAWA, KOICHI TAKAKI, *Iwate University* The two-dimensional array of filaments generated by the self-organizing of atmospheric dielectric-barrier discharges has plasma photonic crystal applications. The net generation time for the self-organization of discharge in one cycle is expected to be short because of its self-extinguishing feature, but that did not happen. However, we attempted to shorten the net generation time by implementing a time difference to drive the parallel array discharge units. The timing of the voltage applied to the discharge cells was controlled by the metal-oxide-semiconductor field-effect-transistors of the circuits, which were turned on by a signal from a single peripheral interface controller. The resultant duty cycles of the discharge current duration per cycle were 6% (single cell), 12% (two parallel cells), and 27% (three parallel cells). When the frequency was changed from 100 to 300 kHz, the generation time increased from 0.61 to 0.72 μs (100 kHz), 0.91 to 1.23 μs (200 kHz), and 1.54 to 1.91 μs (300 kHz). According to these results, frequency and maintenance time are proportional.

*This work was supported by JSPS KAKENHI Grant Numbers 26390094, 24540530.

LW1 53 Generation of atmospheric micro gap radio-frequency discharge plasma under controlled temperature conditions* TAKUMI ARAYA, TAKASHI SHIBATA, HIROKI KIKUCHI, SEIJI MUKAIGAWA, KOICHI TAKAKI, *Iwate University* In dielectric barrier discharge, determining the temperature of a dielectric barrier is difficult owing to a rise in the temperature of a barrier and an electrode because heat generated in a discharge space exhibits a complex local distribution involving gas flow and heat transfer structures. In this study, we examined the effect of dielectric barrier temperature on plasma characteristics and a two-dimensional spatial distribution of the discharge in a radio-frequency atmospheric-pressure plasma. The temperature of the dielectric barrier was kept between 10 °C and 50 °C by circulating hot or cold water in a flow channel in a lower grounded electrode using a cooling water circulating device. Breakdown voltage tended to decrease with an increase in the temperature of the barrier. Depending on an increase in the applied voltage, the discharge aspect was observed to shift to the discharge having two regions, i.e., the bright and dark regions. The area of the bright region increased with an increase in the applied voltage and dielectric barrier temperature. In addition, the current density of the bright region was very high compared with that of the dark region, and therefore, the bright and dark regions were in the glow and Townsend-like modes, respectively.

*This work was supported by JSPS KAKENHI Grant Numbers 26390094, 24540530.

LW1 54 Experiment and modeling of laser photodetachment of negative ions in helium oxygen barrier discharges ROBERT

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TSCHIERSCH, SEBASTIAN NEMSCHOKMICHAL, JÜRGEN MEICHSNER, *Institute of Physics, University of Greifswald* Helium oxygen discharges operating at atmospheric pressure are of great interest for applications, such as surface treatment of biological samples. Helium as the buffer gas keeps the driving power low, and oxygen serves as the source of radicals. The large electronegativity of oxygen results in the formation of negative ions which in turn have a remarkable influence on the discharge development. To point out this role of negative ions, the change of the discharge behavior after the laser photodetachment of negative ions is measured in a helium oxygen barrier discharge. These measurements reveal a lower breakdown voltage when firing the laser during the pre-phase of the discharge. The reason is the additional pre-ionization by the detached electrons which was proved by an 1D numeric fluid modeling. The next step is the determination of absolute number densities of negative ions by a comparison of the experimental parameter variations with those from the modeling. Furthermore, the actual role of negative ions on the discharge behavior will be emphasized by the modeling.

LW1 55 Field-emitting Townsend regime of surface dielectric barrier discharges generated in CO_2 emerging at high pressure* DAVID PAI, *Institut PPRIME* SVEN STAUSS, KAZUO TERASHIMA, *University of Tokyo* Surface dielectric barrier discharges (DBDs) in CO_2 from atmospheric pressure up to supercritical conditions ($T_c = 304.13$ K, $p_c = 7.4$ MPa) generated using 10-kHz ac excitation are studied experimentally. Two discharge regimes are obtained: the standard and field-emitting Townsend regimes. The former resembles typical surface DBDs that have streamer-like characteristics, but the latter has not been reported previously. Here we present an analysis of the electrical and optical diagnostics of the field-emitting Townsend discharge regime using current-voltage and charge-voltage measurements, imaging, optical emission spectroscopy, and spontaneous Raman spectroscopy. Using an electrical model, it is possible to calculate the discharge-induced capacitances of the plasma and the dielectric, as well as the space-averaged values of the surface potential and the potential drop across the discharge. The model also accounts for the space-averaged Laplacian field by including the capacitance due to the fringe electric field from the electrode edge. The electrical characteristics are similar to those of atmospheric-pressure Townsend DBDs, i.e. self-sustained DBDs with minimal space-charge effects. The purely continuum emission spectrum is due to electron-neutral bremsstrahlung, with a corresponding average electron temperature of 2600 K. Raman spectra of CO_2 near the critical point demonstrate that the discharge increases the average gas temperature by less than 1 K.

*This work was supported financially in part by MEXT and JSPS.

LW1 56 Influence of surface processes on surface discharges generated on borosilicate glass barriers in high-pressure CO_2 up to supercritical conditions* DAVID PAI, *Institut PPRIME* SVEN STAUSS, KAZUO TERASHIMA, *University of Tokyo* Surface dielectric barrier discharges (DBDs) generated in CO_2 from atmospheric pressure up to supercritical conditions ($T_c = 304.13$ K, $p_c = 7.4$ MPa) using 10-kHz AC excitation are investigated experimentally using current-voltage and charge-voltage measurements, imaging, and optical emission spectroscopy. Surface processes are investigated to resolve unexplained phenomena from related work on the "standard" and "field-emitting Townsend" discharge regimes. Variations in the energy, residual or "memory" charge, and spatial homogeneity of the field-emitting Townsend regime are shown to depend on the duration that the discharge runs continuously. The memory charge is positive for the field-emitting Townsend regime but negative for the standard regime. It is demonstrated that high discharge homogeneity and low variation in the discharge energy is correlated with the maximization of positive memory charge. Charge neutralization of plasma ions and electrons by anions and cations in the borosilicate glass is proposed as the process responsible for the presence of nanosecond current pulses in the field-emitting Townsend regime.

*This work was supported financially in part by MEXT and JSPS.

LW1 57 Ozone production using dielectric barrier discharge in oxygen and carbon dioxide* FRANCISCO PONTIGA, *University of Seville* ROUKIA ABIDAT, *Université des Frères Mentouri Constantine* HELENA MORENO, FERNÁNDEZ-RUEDA AGUSTÍN, *University of Seville* SAIDA REBIAÏ, *Université des Frères Mentouri Constantine* The generation of ozone in oxygen and carbon dioxide using a planar dielectric barrier discharge (DBD) has been experimentally investigated. The DBD reactor was operated at moderate voltages (4.2 to 5.6 kV) and frequencies (50 to 500 Hz) and the gas flow rate was varied in the range 50 to 200 cm^3/min. The averaged consumed power (<1 W) was evaluated using a monitor capacitor of known capacitance (1 μF). The effluent gas from the DBD reactor was diverted to a gas cell situated inside the sample compartment of a UV spectrophotometer. Therefore, ozone concentration was determined from the measurement of absorbance using Beer-Lambert law. The results have shown that ozone concentration in oxygen grows very linearly with the input power. In contrast, the production of ozone in carbon dioxide is less regular, which may be due to the deposition of a thin layer over the stainless steel electrode during the application of the electrical discharge. Moreover, the rate of ozone production with the injected energy density was found to be 500 times weaker in carbon dioxide than in pure oxygen.

*This work was supported by the Spanish Government Agency "Ministerio de Ciencia e Innovación" under Contract No. FIS2011-25161.

LW1 58 Discharge characteristics and hydrodynamics behaviors of atmospheric plasma jets produced in various gas flow patterns* YUICHI SETSUHARA, GIICHIRO UCHIDA, ATSUSHI NAKAJIMA, KOSUKE TAKENAKA, *Osaka University* KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* Atmospheric nonequilibrium plasma jets have been widely employed in biomedical applications. For biomedical applications, it is an important issue to understand the complicated mechanism of interaction of the plasma jet with liquid. In this study, we present analysis of the discharge characteristics of a plasma jet impinging onto the liquid surface under various gas flow patterns such as laminar and turbulence flows. For this purpose, we analyzed gas flow patters by using a Schlieren gas-flow imaging system in detail The plasma jet impinging into the liquid surface expands along the liquid surface. The diameter of the expanded plasma increases with gas flow rate, which is well explained by an increase in the diameter of the laminar gas-flow channel. When the gas flow rate is further increased, the gas flow mode transits from laminar to turbulence in the gas flow channel, which leads to the shortening of the plasmjet length. Our experiment demonstrated that the gas flow patterns strongly affect the discharge characteristics in the plasma-jet system.

*This study was partly supported by a Grant-in-Aid for Scientific Research on Innovative Areas "Plasma Medical Innovation"

(24108003) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT).

LW1 59 Streamer development in barrier discharge in air: spectral signatures and electric field* TOMAS HODER, *Masaryk University, DPE, Brno, Czech Republic* MILAN SIMEK, *Czech Academy of Sciences, IPP, Prague, Czech Republic* ZDENEK BONAVENTURA, *Masaryk University, DPE, Brno, Czech Republic* VACLAV PRUKNER, *Czech Academy of Sciences, IPP, Prague, Czech Republic* Electrical breakdown in the upper atmosphere takes form of so called Transient Luminous Events (TLE). Down to the certain pressure limit, the first phases of the TLE-phenomena are controlled by the streamer mechanism. In order to understand the development of these events, streamers in 10 torr air were generated in volume barrier discharge. Stability and reproducibility of generated streamers were secured by proper electrode geometry and specific applied voltage waveform. In this work, spectrally resolved measurements of the streamer head emission with high spatial and temporal resolution are presented. Precise recordings of the emission of the second positive and first negative systems of molecular nitrogen allowed the determination of the spatio-temporal development of the reduced electric field in the streamer head. This unique experimental result reveals in more details the early stages of the streamer development and gives, besides values for streamer velocity and its diameter, quantitative information on the magnitude of the electric field.

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LW1 60 PIC-DSMC analysis on interaction of a laser induced discharge and shock wave* KOHEI SHIMAMURA, *University of Tsukuba* Laser induced discharge and the shock wave have attracted great interest for use in the electrical engineering. When the high intensity laser (10 GW >) is focused in the atmosphere, the breakdown occurs and the discharge wave propagates toward to the laser irradiation. The shock wave is generated around the discharge wave, which is called as the laser supported detonation wave. After breakdown occurred, the initial electron of the avalanche ionization is produced by the photoionization due to the plasma radiation. It is well recognized that the radiation of the laser plasma affects the propagation mechanism of the laser induced discharge wave after the initiation of the breakdown. However, it is difficult to observe the interaction between the plasma radiation and the electron avalanche in the ionization-wave front in experimentally except in the high intensity laser. In the numerical calculation of the laser-induced discharge, the fluid dynamics based on the Navier-Stokes equation have been widely used. However, it is difficult to investigate the avalanche ionization at the wave front using the fluid dynamics simulation. To investigate the interaction of the ionization-wave front and the shock wave, it is appropriate to utilize the PIC-DSMC method. The present study showed the propagation of the ionization front of the discharge wave and the shock wave using the particle simulation.

*This work was supported by Kato Foundation for Promotion of Science and Japan Power Academy.

LW1 61 Streamer properties in a repetitively pulsed plasma jet from 1 to 100 kHz* BRIAN SANDS, *UES, Inc. (AFRL)* BISWA GANGULY, *Retired* JAMES SCOFIELD, *Air Force Research Laboratory* We investigate the properties of guided streamers in a nanosecond repetitively pulsed dielectric barrier plasma jet at repetition rates up to 100 kHz. In this regime, remnant ionization and neutral metastable concentrations are significant in the channel through which the streamer propagates. Both helium and a Penning mixture of helium and argon are investigated as feed gases for a plasma jet in a controlled pressure chamber with a flowing nitrogen background. The applied voltage pulse was set at 8 kV, with a risetime of 15 ns and falltime of 8.5 μs. Streamer dynamics were monitored using spatiotemporally-resolved emission spectroscopy with a PMT filtered at 706.5 nm He (3^3S - 2^3P) and 587.6 nm He (3^3D - 2^3P) to track the streamer head. Temporally-resolved ICCD imaging was also used to characterize discharge development. Tunable diode laser absorption spectroscopy was used to measure He (2^3S_1) and Ar ($^3P_2$) metastable densities in the streamer channel, and streamer current was measured using an inductive current monitor. As the pulse rate is increased, the streamer dynamics are significantly altered, while production of He (2^3S_1) and Ar ($^3P_2$) is enhanced with alternate production channels becoming important in the case of He (2^3S_1).

*Work funded by Air Force Office of Scientific Research under program manager Jason Marshall.

LW1 62 Influence of dielectric materials on radial uniformity in non-equilibrium atmospheric pressure helium plasma* AKINORI ODA, *Faculty of Engineering, Chiba Institute of Technology* KYOHEI KOMORI, *Graduate School of Engineering, Chiba Institute of Technology* Non-equilibrium atmospheric pressure plasma has been utilized for various technological applications such as surface treatment, materials processing, bio-medical and bio-logical applications. For optimum control of the plasma for the above applications, numerous experimental and theoretical investigations on the plasma have been reported. Especially, controlling radial uniformity of the plasma are very important for utilizing materials processing. In this paper, an axially-symmetric three-dimensional fluid model, which is composed of the continuity equation for charged and neutral species, the Poisson equation, and the energy conservation equation for electrons, of non-equilibrium atmospheric pressure helium plasma has been developed. Then, influence of dielectric properties (e.g. relative permittivity, secondary electron emission coefficient, etc.) of dielectric materials on radial plasma uniformity (i.e. radial distributions of electron density, ion density, electric field in the plasma) was examined.

*This work was partly supported by KAKENHI (No. 26420247), and a "Grant for Advanced Industrial Technology Development (No. 11B06004d)" in 2011 from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

LW1 63 High Power Helicon Plasma Source for Plasma Processing JAMES PRAGER, TIMOTHY ZIEMBA, KENNETH E. MILLER, *Eagle Harbor Technologies, Inc.* Eagle Harbor Technologies (EHT), Inc. is developing a high power helicon plasma source. The high power nature and pulsed neutral gas make this source unique compared to traditional helicon source. These properties produce a plasma flow along the magnetic field lines, and therefore allow the source to be decoupled from the reaction chamber. Neutral gas can be injected downstream, which allows for precision control of the ion-neutral ratio at the surface of the sample. Although operated at high power, the source has demonstrated very low impurity production. This source has applications to

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nanoparticle productions, surface modification, and ionized physical vapor deposition.

LW1 64 Spectroscopic Investigation of a Dielectric Barrier Discharge Over a Wide Range of Pulse Parameters JULIAN PICARD, JAMES PRAGER, TIMOTHY ZIEMBA, KENNETH E. MILLER, AKEL HASHIM, *Eagle Harbor Technologies, Inc.* Most high voltage pulser used to drive dielectric barrier discharges (DBDs), produce a single pulse shape (width and voltage), thus making it challenging to assess the effect of pulse shape on the production of different chemical species during a discharge. Eagle Harbor Technologies (EHT), Inc. has developed a nanosecond pulser that allows for independent control of the output voltage, pulse width, and pulse repetition frequency. Through the utilization of this technology, presented here is a precise characterization of reactive species generated by the DBD under the independent variation of voltage (0-20 kV), frequency (0-20 kHz) and pulse width (20-260 ns). A better understanding of this parameter dependency can allow for more targeted and effective application of plasma in medical, environmental, industrial, and other applications.

LW1 65 Surface treatment of a titanium implant using low temperature atmospheric pressure plasmas HYUN-YOUNG LEE, TIANYU TANG, *Pusan National University* JUNG-WOO OK, *Korea Basic Science Institute* DONG-HYUN KIM, HO-JUN LEE, HAE JUNE LEE, *Pusan National University* During the last two decades, atmospheric pressure plasmas(APP) are widely used in diverse fields of biomedical applications, reduction of pollutants, and surface treatment of materials. Applications of APP to titanium surface of dental implants is steadily increasing as it renders surfaces wettability and modifies the oxide layer of titanium that hinders the interaction with cells and proteins. In this study, we have treated the titanium surfaces of screw-shaped implant samples using a plasma jet which is composed of a ceramic coaxial tube of dielectrics, a stainless steel inner electrode, and a coper tube outer electrode. The plasma ignition occurred with Ar gas flow between two coaxial metal electrodes and a sinusoidal bias voltage of 3 kV with a frequency of 20 kHz. Titanium materials used in this study are screw-shaped implants of which diameter and length are 5 mm and 13 mm, respectively. Samples were mounted at a distance of 5 mm below the plasma source, and the plasma treatment time was set to 3 min. The wettability of titanium surface was measured by the moving speed of water on its surface, which is enhanced by plasma treatment. The surface roughness was also measured by atomic force microscopy. The optimal condition for wettability change is discussed.

LW1 66 Laser diagnostics on atmospheric-pressure low-temperature helium pulsed plasmas in room- and cryogenic-temperature environments NORITAKA SAKAKIBARA, HITOSHI MUNEOKA, KEIICHIRO URABE, RYOMA YASUI, KAZUO TERASHIMA, *The University of Tokyo* In atmospheric-pressure low- temperature plasmas, the control of the plasma gas temperature (T_g) by a few kelvin is considered to be crucial for their applications to novel materials processing such as bio-materials. However, there have been only few studies that focused on the influence of T_g on the plasma characteristics. On the other hand, it was reported that helium metastables played a key role in the dependency of chemical reactions on T_g in helium-nitrogen plasmas. In this study, laser diagnostics were carried out in atmospheric-pressure helium pulsed plasmas near or below room temperature, at 340–100 K. Parallel electrodes of copper rods (diameter: 2 mm) with a gap distance of 535 μm were used and pulsed discharges with a pulse width of a few hundred nanoseconds were generated inside a reactor. The density and lifetime of helium metastables were estimated by laser absorption spectroscopy measurements and T_g was evaluated by near-infrared laser heterodyne interferometry measurements. At 300 K, the helium metastable density was 1.5×10^{13} cm^{-3} while the lifetime was 3.1 μs, and increase in T_g was up to 70 K. Dependency of the density and lifetime of helium metastables on T_g was observed and also discussed.

LW1 67 Effect of the Discharge Voltage on the Performance of the Hall Thruster PING DUAN, AN-NING CAO, GUANG-RUI LIU, XING-YU BIAN, YAN YIN, *Dalian Maritime University* LONG CHEN, *Dalian University of Technology* A two-dimensional physical model is established according to the discharging process in the Hall thruster discharge channel. By using particle-in-cell method, the influences of the discharge voltage on the distribution of the potential, ion number density, electron temperature and ion radial velocity are investigated in a fixed magnetic field configuration, and the reason of discharge current increasement along with discharge voltage is also analyzed. It is found that, while the discharge voltage increases during 250-650V, the distribution of electric potential has a small expansion towards anode in axis direction, the ion radial velocity at the exit is reduced, and collision frequency between ions and wall surface is also decreased. Meanwhile, the saturation of electron temperature is observed when discharge voltage is in the range of 400-450V, and the electron temperature decreases. When the discharge voltage increases to 700V, the distribution of potential expands towards anode in axis direction significantly, the acceleration region length is greatly increased, the ionization region is compressed to the vicinity of anode, the ion radial velocity near the wall increases and collision frequency between ions and wall surface is enhanced. As the increasement of near wall conductive current and high energy electron number inside the discharge channel, the discharge current increases monotonously with the increase of discharge voltage.

LW1 68 MICRODISCHARGES, DC, RF, MICROWAVE

LW1 69 Microplasma deposition of challenging thin films at atmospheric pressure JEFFREY HOPWOOD, H.C. THEJASWINI, *Tufts University* PLASMA ENGINEERING LABORATORY TEAM Non-equilibrium microplasmas produce fluxes of ions and excited species to a surface while maintaining the surface near room temperature. At atmospheric pressure, however, it is very difficult to accelerate the highly collisional ions. While many applications do not benefit from energetic interactions between plasma and surface, conventional plasma deposition of thin films often requires either ion bombardment or substrate heating. For example, diamondlike carbon (DLC) is known to require ~ 100 eV ion bombardment and transparent conducting oxides (TCO) typically require substrate temperatures on the order of 400-500 K. A microwave-induced microplasma is used to dissociate dilute precursor molecules within flowing helium. The precursor and plasma species result in rapid deposition of thin films (>1 μm/min). This plasma produces a steady-state ion flux of 6×10^{17} cm^{-2}s^{-1}, which is more than two orders of magnitude greater than a low pressure capacitively coupled plasma. Likewise, the metastable density is roughly two orders greater. These and other microplasma diagnostics are correlated with the measured film properties of microplasma-deposited DLC and TCO. This study shows that high ion flux, even at low energy (∼ 1 eV), can provide the needed surface interactions to produce these materials at room temperature.

LW1 70 Breakdown of atmospheric pressure microgaps at high excitation frequencies* DMITRY LEVKO, LAXMINARAYAN RAJA, *The University of Texas at Austin* Microwave breakdown of atmospheric pressure microgaps was studied by a one-dimensional Particle-in-Cell Monte Carlo Collisions numerical model. The effect of both field electron emission and secondary electron emission (due to electron impact, ion impact, and primary electron reflection) from surfaces on the breakdown process is considered. For conditions where field emission is the dominant electron emission mechanism from the electrode surfaces, it is found that the breakdown voltage of mw microdischarge coincides with the breakdown voltage of direct-current microdischarge. When microdischarge properties are controlled by both field and secondary electron emission, breakdown voltage of mw microdischarge exceeds that of dc microdischarge. When microdischarge is controlled only by secondary electron emission, breakdown voltage of mw microdischarge is smaller than that of dc microdischarge. It is shown that if the interelectrode gap exceeds some critical value, mw microdischarge can be ignited only by electrons initially seeded within the gap volume. In addition, the influence of electron reflection and secondary emission due to electron impact is studied.

*This work was supported by the Air Force Office of Scientific Research.

LW1 71 Study of microplasmas from GHz to THz JOSÉ GREGÓRIO, ALAN R. HOSKINSON, STEPHEN PARSONS, JEFFREY HOPWOOD, *Tufts University* We present a study of atmospheric-pressure microplasmas sustained from 0.5 GHz to 0.5 THz with continuous excitation frequencies. A fluid model shows the existence of electron plasma resonances in a highly collisional microplasma. At 0.5 GHz the behavior is similar to a typical rf collisional discharge. As frequency increases at constant power density we observe a decrease in the discharge voltage from greater than 100 volts to less than 10 volts. This minimum voltage amplitude is attained when electron temporal inertia delays the discharge current to be in phase with the applied voltage. Above this frequency the plasma develops resonant regions where the excitation frequency equals the local plasma frequency. In these volumes the instantaneous quasi-neutrality is perturbed and intense internal currents emerge ensuring a low voltage operation range. This enhanced plasma heating mechanism vanishes when the excitation frequency is larger than the local plasma frequency everywhere in the plasma volume. For a typical peak electron density of 5×10^{20} m^{-3} this condition corresponds to ∼ 0.2 THz.

LW1 72 Spaceresolved determination the features and parameters of plasmoids obtained by gyromagnetic autoresonance. DENIS CHUPROV, VICTOR ANDREEV, ANATOLIY UMNOV, ANDREY NOVITSKII, *PFUR* Experiment and computer simulation with relativistic plasma obtained under gyromagnetic autoresonance (GA) condition are described. X-ray spectrometry, radiometry and imaging methods were applied to investigate obtained plasmoids. Energies of measured bremsstrahlung spectrums up to 0,5 MeV were observed. Investigation of the spatial anisotropy of produced X-ray radiation gave information about the plasmoid shape, localization and movement. The complex motion of the belt shaped relativistic plasmoid can be presented as rotation of the driving center around trap symmetry axis. Obtained experimental results are in good quantitative agreement with numerical simulations of GA process by particles-in-cell model.

LW1 73 Scaling of Small Arrays of Microplasmas* CHENHUI QU, PENG TIAN, MARK J. KUSHNER, *University of Michigan* Arrays of microplasmas have meta-material capabilities that enable altering the properties of incident electromagnetic waves. The desirable properties of these microplasma arrays (MPAs) are high plasma density, rapid re-configuration and a minimum of isolating structures between microplasma elements that might perturb the dielectric properties of the array. These attributes are in part achieved by tradeoffs between gas mixture, pressure and pulse-power waveform. In this paper, results from a computational investigation of MPAs sustained in rare gas mixtures will be discussed. A 2-dimensional plasma hydrodynamics model with radiation transport was used to investigate the ability to modulate the permittivity of small MPAs – up to 4 × 4 elements. Gas pressures are tens to hundreds of Torr in mixtures of rare gases (e.g., Ar/Xe). We found that in the absence of isolating structures, there is significant cross talk between the elements of the MPAs when using repetitive uni- and bi-polar pulses (tens to hundreds ns duration). For example, when alternate elements of the array are pulsed, unpowered electrodes of adjacent pixels may appear cathodic or anodic to its neighbors, thereby attracting current through the unpowered pixel.

*Work supported by DARPA, DOE (DE-SC0001319), and NSF (CHE-1124724).

LW1 74 Effect of external floating electrode for enhancing efficiency of generating an atmospheric pressure inductively coupled microplasma* KATSUKI TUKASAKI, SHINYA KUMAGAI, MINORU SASAKI, *Toyota Technological Institute* TOYOTA TECHNOLOGICAL INSTITUTE TEAM To make a plasma source which can generate a microplasma at low power without using an ignitor (ex. high-voltage power supply), we have used an electrically floating electrode inside a glass tube surrounded by an antenna coil of inductive coupling [1]. Helium gas was fed into the glass tube. When VHF power was supplied to the antenna coil, the floating electrode reached electrically high potential and an atmospheric pressure inductively coupled microplasma was generated. The ignition power depended on the length of the floating electrode further. The longer the length was, the less ignition power was. To make the plasma source compact, the floating electrode was moved outside the glass tube (O.D. 1.5mm, I.D. 1mm) while only a part of floating electrode (Ni wire, 10mm, ϕ 0.3mm) was remained inside the glass tube. Both the cable and Ni wire was magnetically connected to each other through the wall of glass tube. With changing the cable length, ignition power was measured. The ignition power varied with the unit of half wavelength of the VHF. The wavelength resonance effect decreased the ignition power.

*This study was supported by MEXT program for Forming Strategic Research Infrastructure (S1101028) Japan.

[1]Asano *et al.*, Jpn. J. Appl. Phys. **51**, 011AA01 (2012).

LW1 75 Design and Use of a Microdischarge of Argon in a Liquids GERARDO RUIZ VARGAS, ANTONIO JUÁREZ REYES, *UNAM* We have designed and implemented a pulsed micro-plasma of Argon with a liquid electrode. The system allows to detect metallic compounds dissolved in water. The microplasma is used as a

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source of excitation source and the discharge operates at atmospheric pressure according to the Paschen law. Coupling a CCD monochromator of our design to the microplasma source with liquid electrode, we are able to carry out emission spectroscopy of the excited species present in the sample. For the proof of concept test of this instrument we used a dissolved solution, in the milli-mol range of $HgCl_2$ which is one of the water soluble forms of mercury. This experimental setup is able to detect lower concentrations of Hg in the range of 10 mili-mol. This device is designed to be placed on a sample of water and perform in situ measurement. We design a chamber in which the micro-electrodes are connected to a ventury. The pressure drop in the ventury is achieved with the flow of Argon. With this arrange it is possible to carry the water from a container to inside de chamber into the space between two electrodes. One of these electrodes is submerged in water (liquid electrode) and the other exposed to Argon. Mercury has very intense peaks in 253.65 nm and 435.8 nm, and less intense in 365.01 nm and 546.07 nm. Argon, the drag gas and discharge gas, emits an intense peak at 350 nm. Two emission peaks in mercury at 253.65 nm and 440 nm are visible with our arrangement. From the intensity of the emission lines it is possible to determine their concentration in water.

LW1 76 THERMAL PLASMAS: ARCS, JETS, SWITCHES, OTHERS

LW1 77 Analyzing spotless mode of current transfer to cathodes of Cr, Gd, and Pb vapour arcs* LARISSA BENILOVA, MIKHAIL BENILOV, *Departamento de Física, CCCEE, Universidade da Madeira and Instituto de Plasmas e Fusão Nuclear, IST, Universidade de Lisboa, Portugal* Diffuse mode of current transfer occurs on cathodes of vacuum arcs if the average cathode surface temperature is high enough, which can be achieved by placing the (evaporating) cathode into a thermally insulated crucible. It is shown that in the case of Cr or Pb cathodes the usual mechanism of current transfer to arc cathodes cannot sustain current densities of the order of $10^5 - 10^6 \mathrm{Am}^{-2}$ observed in the experiment, the reason being that the electrical power deposited into electron gas in the near-cathode space-charge sheath is too low. It is hypothesized that the electrical power is supplied to the electron gas primarily in the bulk plasma, rather than in the sheath, and a high level of electron energy at the sheath edge is sustained by electron heat conduction from the bulk plasma. Estimates of the current of ions diffusing to the sheath edge from the quasi-neutral plasma gave values comparable to the experimental current density, which supports the above hypothesis. On the contrary, the spotless attachment of vacuum arcs to Gd cathodes may be interpreted as a manifestation of the usual arc cathode mechanism. Results given for Gd cathodes by a model of near-cathode layers in vacuum arcs conform to available experimental information.

*Work supported by FCT of Portugal through the projects PTDC/FIS-PLA/2708/2012 and Pest-OE/UID/FIS/50010/2013.

LW1 78 Synthesis of Amorphous Alloy Nanoparticles by Thermal Plasma Jet in a Quenching Tube SOOSEOK CHOI, *Jeju National University* DONG-WHA PARK, *Inha University* Recently, amorphous alloy nanoparticles have received a great attention in various applications such as catalysts, compact and highly efficient transformers, electrode material for Li-ion batteries, etc. Several methods such as microwave heating, laser ablation, and sonification have been studied to synthesize amorphous metal nanoparticles. In the present work, a high velocity thermal plasma jet generated by an arc plasma torch was used to produce iron alloy nanoparticles from an amorphous raw material which was a spherical shaped powder with the mean size of 25 μm. In order to synthesize amorphous alloy nanoparticles, a quenching tube where cooling gas was injected in different axial positions. Alloy nanoparticles were produced in a relatively high input power of higher than 10 kW in a fixed powder feeding at 300 mg/min. The crystallinity of synthesized nanoparticles was decreased with increasing the quenching gas flow rate. The amorphous alloy nanoparticles were found when the quenching gas injection position was 200 mm away from the exit of the plasma torch with the highest quenching gas flow rate of 20 L/min. In the numerical analysis, the highest quenching rate was also expected at the same condition.

LW1 79 Multi-electrodes Atmospheric Pressure Plasma Jet Aiming Bio-applications JEON G. HAN, B.B. SAHU, K.S. SHIN, J.S. LEE, *NU-SKKU Joint Institute for Plasma Nano Materials, Center for Advanced Plasma Surface Technology, Sungkyunkwan University, Korea* M. HORI, *Plama Nanotechnology Research Center, Nagoya University, Nagoya, Japan* For the recent advancement in the field of plasma medicine, there is growing demand for the atmospheric-pressure plasma (APP) jet sources with desired plasma characteristics. In this study, a stable non-thermal low-voltage APP jet device was designed and developed for optical and electrical characterizations. The jet was operated at very low frequency in the range 10-40 KHz, which enabled the generation of low power ($\sim$ 7W) plasma with a plasma column diameter of about 5 mm. The jet has a visible radial diameter of approximately 10 mm. Optical emission spectroscopy was used as a diagnostic tool to investigate the generation of plasmas and radical species. Discharge parameters are also measured to evaluate the different operating conditions. The gas temperature measured at the substrate location varies from 300 to 315 K for different gases where the electrical input power ranged from 1 to 7 W. The highly reactive species like OH, O, N2, N2+ and along with the trace of NO are characterized with respect to the different gas flow rate of Ar/He/O2/N2, applied voltages, duty cycles and frequencies to evaluate the capability of the APP jet for future bio-applications.

LW1 80 Synthesis of Lithium Oxide Composite Nanoparticles with Spinel Structure by Induction Thermal Plasma TAKUYA KAGEYAMA, HIROTAKA SONE, *Department of Chemical Systems and Engineering, Kyushu University* MANABU TANAKA, *Department of Chemical Engineering, Kyushu University* DAISUKE OKAMOTO, *Department of Chemical Systems and Engineering, Kyushu University* TAKAYUKI WATANABE, *Department of Chemical Engineering, Kyushu University* Lithium oxide composite nanoparticles were successfully synthesized by induction thermal plasma. Powder mixtures of Li_2CO_3 and MnO_2 were injected into the induction thermal plasma at 20 kW-4MHz operated in different O_2 gas flow rates. The injected precursors were evaporated immediately in the high temperature region of the plasma and nanoparticles were produced through the quenching process. The particles were characterized by using X-ray diffraction (XRD) and transmission electron microscopy (TEM). The obtained results indicated that the nanoparticles of $LiMn_2O_4$ and $LiMnO_2$ were selectively synthesized by controlling partial pressure of O_2 in thermal plasma. Then formation mechanism of Li-based oxide nanoparticles was investigated on the basis of homogenous nucleation rate and thermodynamic consideration. In higher partial pressure of O_2, MnO nucleates and Li oxide condense on the nuclei with relatively high condensation rate, resulting in single-phase $LiMn_2O_4$ formation. On the other hand, in lower partial pressure of

O_2, $LiMnO_2$ was obtained due to the lower condensation rate of Li oxide.

LW1 81 Effect of Lightning Impulse Discharge on PVC Thin Film NORIMITSU TAKAMURA, TAKAO MATSUMOTO, *Department of Electrical Engineering, Fukuoka University* HAZUKI NEROME, KENJI MISHIMA, *Department of Chemical Engineering, Fukuoka University* YASUJI IZAWA, MASAHIRO HANAI, KIYOTO NISHIJIMA, *Department of Electrical Engineering, Fukuoka University* Lightning damage to blades of wind turbine generators has been increasing in parallel with the recent increase in the installation of the generators. According to a paper, it is said that a large current produced by a lightning penetrates into the blades, the air temperature and pressure inside the blades increase, which causes destruction of the blades. In order to solve this problem, preventing lightning penetration into the blades and passing lightning only on the surface of the blades are required. Therefore, we undertook a basic research for finding out the mechanism of lightning penetration into the blades. In this study, as our original research for clarifying the above mechanism, we investigated the effect of lightning impulse discharge on some polyvinyl chloride thin films. A high voltage electrode and a ground electrode were set with 1.0 m separation. Each film was set at the midpoint of the electrodes and approximately 750 kV of only one positive lightning impulse voltage was applied to the electrodes. After discharge, the hole-, deformed- and tarnished- diameters of the films, formed by discharge, were measured using a microscope. The results suggest that the thickness and/or the volume resistivity of the films are deeply tied to destruction of the films by discharge.

LW1 82 Synthesis of Core-shell Structured Amorphous Si Nanoparticles by Induction Thermal Plasmas DAISUKE OKAMOTO, TAKUYA KAGEYAMA, *Department of Chemical Systems and Engineering, Kyushu Univeristy* MANABU TANAKA, *Department of Chemical Enginerring, Kyushu University* HIROTAKA SONE, *Department of Chemical Systems and Engineering, Kyushu Univeristy* TAKAYUKI WATANABE, *Department of Chemical Enginerring, Kyushu University* Core-shell structured amorphous Si nanoparticles were synthesized by induction thermal plasma. Crystalline Si powder with 3 μm of average diameter was injected into the induction thermal plasma at 4 MHz. The Si raw materials immediately evaporate in the high temperature plasma region and nanoparticles were produced through the quenching process. Counterflow quenching gas was injected from downstream of the torch with its direction against the plasma flow. The effect of the operating parameter such as flow rate of quenching gas and input power was investigated. Collected particles were characterized by X-ray diffraction, transmission electron microscopy, electron energy-loss spectroscopy, and Raman spectroscopy. Obtained results indicate that amorphization degree of the synthesized nanoparticles is more than 90% when additional quenching gas of 20 L/min is injected. The quenching rate of the prepared nanoparticles in the growth region have an important role on determining the amorphization degree. Moreover, EELS and Raman analyses showed the synthesized nanoparticles were coated by the SiO_2 shell with thickness of 2-4 nm. These findings indicated that amorphous Si/SiO_2 core-shell structured nanoparticles were successfully synthesized by induction thermal plasma in single step.

LW1 83 Prediction of SFL Interruption Performance from the Results of Arc Simulation during High-Current Phase JONG-CHUL LEE, WON-HO LEE, *Gangneung-Wonju National University* WOUN-JEA KIM, *Sungkyunkwan University* The design and development procedures of SF_6 gas circuit breakers are still largely based on trial and error through testing although the development costs go higher every year. The computation cannot cover the testing satisfactorily because all the real processes arc not taken into account. But the knowledge of the arc behavior and the prediction of the thermal-flow inside the interrupters by numerical simulations are more useful than those by experiments due to the difficulties to obtain physical quantities experimentally and the reduction of computational costs in recent years. In this paper, in order to get further information into the interruption process of a SF_6 self-blast interrupter, which is based on a combination of thermal expansion and the arc rotation principle, gas flow simulations with a CFD-arc modeling are performed during the whole switching process such as high-current period, pre-current zero period, and current-zero period. Through the complete work, the pressure-rise and the ramp of the pressure inside the chamber before current zero as well as the post-arc current after current zero should be a good criterion to predict the short-line fault interruption performance of interrupters.

LW1 84 Three-Dimensional Numerical Modeling of Free-Burning Arcs Using a CFD-MHD Coupled Method JONG-CHUL LEE, WON-HO LEE, *Gangneung-Wonju National University* YOUN-JEA KIM, *Sungkyunkwan University* Because a scientific understanding of the thermal behavior of arcs and their electrodes in free-burning arc systems is very important for improving industrial applications, numerous theoretical and experimental papers have been published in the last decade. However, the flow patterns inside the free-burning arc system must be of the 3-D feature, and 2-D modeling cannot help in predicting the 3-D flow and heat transfer within the system. This paper is concerned with developing a capability to model free-burning high-intensity argon arcs (self-consistent model) and enhancing the accuracy of numerical results according to three-dimensional calculations. It was found that the computed temperatures along the axis between the cathode tip and the anode surface show good agreement with two different measured data. Although the LTE model can reasonably predict the overall arc voltage for free-burning arcs, it fails to account accurately what happens at the near electrode region. An accurate solution near electrodes has to be based on non-LTE model to ensure current continuation in the low temperature region. Calculation of the energy flux towards the anode also requires the mechanisms operating in the non-LTE situation be taken into account in the model.

LW1 85 PLASMAS IN LIQUIDS

LW1 86 Generation of Radio Frequency Plasmas in Pure Water within Hole in Insulating Plate TSUNEHIRO MAEHARA, *Ehime University* SHINYA MATSUTOMO, *National Institute of Technology, Niihama College* SHIN YAMAMOTO, SHINOBU MUKASA, AYAKA TANAKA, AYATO KAWASHIMA, *Ehime University* Recently, various types of plasmas in water have been investigated. In some cases, it has been observed that plasmas in water are not in contact with the metal electrodes. In these systems, no metal electrodes contaminate water. Our research group has carried out experimental investigations on RF plasma enclosed in a bubble within a hole in an insulating plate. RF power was applied between two electrodes, and an insulating plate was placed between them. RF plasmas in pure water (0.2mS/m) and 1 wt% NaCl solution can be generated within the hole, apart from the electrodes. When hole diameter is 3-10 mm, the plasmas can be maintained stably. From finite element method, the electric field and heat density before breakdown were estimated,

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and on the basis of those calculations it was shown that bubble formation is a key factor for plasma generation, that is, in both the cases, the existence of a bubble increases the electric field at the side of the bubble increases. These facts suggest plasma generation occurs at around the side of the bubble. However, solution can be treated as a conductor in 1 wt% NaCl solution. On the other hand, in pure water, water behaves as an insulator. Therefore, different mechanisms lead to the plasma generation.

LW1 87 Characteristics of Solution Plasma Generated with Coaxial DBD KENTARO NISHIMOTO, KENJI TANAKA, TATSURU SHIRAFUJI, *Osaka City University* SHIN-ICHI IMAI, *Panasonic Corporation* Recently, solution plasma processing, or plasma processing in or in contact with an aqueous solution, has attracted much attention because of its various possible applications. Although different types of plasma generation methods have been proposed, most of them do not cover a wide range of electrical conductivity of the water to be treated. Since the water subjected to the plasma treatment can have any values of electrical conductivity depending on the purposes of treatments, we must develop methods that cover a wide range of electrical conductivity of water. The conventional solution plasma has shown a strong dependence on the electrical conductivity of water, in which stable discharge is available only in the water with an electrical conductivity of 100 ± 50 μS/cm. The coaxial-type DBD in contrast has shown intense discharge within the conductivity range of 0.5-160 μS/cm. This result indicates that the coaxial type DBD has more "robust" dependence on the electrical conductivity of water. Furthermore, the coaxial type DBD has shown 3-fold higher energy efficiency in indigo carmine degradation than the conventional solution plasma.

LW1 88 Mechanisms of Methylene Blue Degradation in Three-dimensionally Integrated Micro-solution Plasma AYANO NOMURA, *Osaka City University* YUI HAYASHI, *Nagoya University* KENJI TANAKA, TATSURU SHIRAFUJI, *Osaka City University* MOTONOBU GOTO, *Nagoya University* Plasma in aqueous solution has attracted much attention because they are expected to have possibilities to solve water-related environmental issues. In such application-oriented researches, degradation of methylene blue (MB) or other organic dyes has been widely used for investigating the effects of the plasma treatment on the water with organic contaminants. However, there are few reports on the detailed analysis of the products after the plasma treatment of MB aqueous solution for understanding mechanisms of the degradation processes. We have hence analyzed our degradation products using matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) mass spectrometry. We have performed the MB degradation in three-dimensionally integrated micro-solution plasma, which has shown 16-fold higher performance in MB degradation than conventional solution plasma. The results of MALDI-TOF mass spectrometry have indicated the formation of sulfoxides in the first stage of the degradation. Then, the methyl groups on the sulfoxides are partially oxidized. The sulfoxides are separated to form two benzene derivatives after that. Finally, weak functional groups are removed from the benzene derivatives.

LW1 89 Time-resolved Optical Emission Spectroscopy on DBD of Ar Gas in Contact with Water KAZUHIKO OBANA, KENJI TANAKA, TATSURU SHIRAFUJI, *Osaka City University* Recently, we have proposed three-dimensionally integrated micro-solution plasma (3D IMSP) to perform plasma treatment on a large amount of aqueous solution. In a 3D IMSP reactor, many microplasmas are generated in a porous dielectric material filled with a gas-liquid mixed medium. Time-resolved optical emission spectroscopy (OES) on 3D IMSP has revealed that the emission intensity of OH (A-X) shows unique and interesting behavior as a function of time. The OES data, however, are not those for one bubble but are averages for spatially distributed bubbles. To improve the performance of 3D IMSP, we should understand the details of plasma in one bubble. We have hence investigated the plasma generated in a simple reactor that is considered to have an environment equivalent to one bubble in 3D IMSP. The reactor has a configuration to drive dielectric barrier discharge (DBD) of Ar gas in contact with water, on which we have performed OES. The OES results have shown that the optical emission of OH (A-X) lasts longer than that of Ar. We discuss its possible mechanisms together with numerical simulation of the DBD and detailed analysis of the spectral profiles of the OH (A-X) emission.

LW1 90 Gold Nanoparticle Synthesis by 3D Integrated Micro-solution Plasma in a 3D Printed Artificial Porous Dielectric Material NAOYA SOTODA, KENJI TANAKA, TATSURU SHIRAFUJI, *Osaka City University* Plasma in contact with $HAuCl_4$ aqueous solution can promote the synthesis of gold nanoparticles. To scale up this process, we have developed 3D integrated micro-solution plasma (3D IMSP). It can generate a large number of argon microplasmas in contact with the aqueous solution flowing in a porous dielectric material. The porous dielectric material in our prototype 3D IMSP reactor, however, consists of non-regularly arranged random-sized pores. These pore parameters may be the parameters for controlling the size and dispersion of synthesized gold nanoparticles. We have hence fabricated a 3D IMSP reactor with an artificial porous dielectric material that has regularly arranged same-sized pores by using a 3D printer. We have applied the reactor to the gold- nanoparticle synthesis. We have confirmed the synthesis of gold nanoparticles through the observation of a plasmon resonance absorption peak at 550 nm in the $HAuCl_4$ aqueous solution treated with 3D IMSP. The size and distribution of the synthesized gold nanoparticles are under investigation. We expect that these characteristics of the gold nanoparticles can be manipulated by changing pore size and their distribution in the porous dielectric material.

LW1 91 Sterilization of *E. coli* Using 3D Integrated Micro-solution Plasma JUNPEI YAMAMOTO, KENJI TANAKA, TATSURU SHIRAFUJI, TAKESHI NAKANISHI, MASAYA KITAMURA, *Osaka City University* Recently, sterilization of water using plasma has attracted much attention. In most cases, however, the plasma in water is quite smaller than the volume of water. To industrialize the sterilization of water using plasma, we must have appropriate plasma sources for the treatment of large-volume water. Previously, we have developed a novel reactor utilizing three-dimensionally integrated micro-solution plasma (3D IMSP). 3D IMSP generates a large number of microplasmas in contact with the aqueous solution flowing in a porous dielectric material. The 3D IMSP reactor has shown superior performance in methylene blue degradation than a conventional reactor that generates plasma between two stylus electrodes in the water. In this work, we have applied the novel 3D IMSP to the sterilization of *E. coli*, and confirmed that we can sterilize the water of 150 mL with *E. coli* of 10^6 cells/mL within 6 min. We have also observed almost the same results when we treat the *E. coli* with the water treated with the 3D

IMSP. We discuss the possibility of the contribution of H_2O_2 and/or the other factors in our sterilization process.

LW1 92 Development of High-Throughput Liquid Treatment System using Slot Antenna Excited Microwave Plasma SHO TAKITOU, *Ngoya Univ.* MICHIKO ITO, *Ngoya Univ. Plama Center for Industrial Applications* SEIGOU TAKASHIMA, *Plasma Center for Industrial Applications* NORIO NOMURA, TOMINORI KITAGAWA, *Sanshin Mgf. Co., Ltd* HIROTAKA TOYODA, *Ngoya Univ., PLANT, Nagoya Univ.* Recently, much attention has been given to plasma production under liquid and its industrial applications as well as investigation of chemical reactions as a result of plasma-liquid interactions. In various kinds of plasma production techniques, we have proposed pulsed microwave excited plasma using slot antenna, where damage to the slot electrode can be minimized and plasma volume can be increased. Furthermore, we have proposed an in-line microwave plasma system where plasma is efficiently produced under reduced pressures using Venturi effect, and have demonstrated enhancement of organic decomposition efficiency. For practical use of the plasma liquid treatment, however, cost-effective and more efficient treatment system with high treatment capability is required. In this study, we propose further enhancement of the treatment speed by designing four-parallel-type liquid treatment device where four discharges for the treatment are performed using one microwave power source. Decomposition speed of newly-developed plasma system is investigated. Not only high decomposition rate but also enhanced energy efficiency is realized.

LW1 93 Organic Decomposition Performance of In-line Liquid Treatment System Using Microwave Plasma MICHIKO ITO, *Nagoya University, Plasma Center for Industrial Applications* SEIGO TAKASHIMA, *Plasma Center for Industrial Applications* NORIO NOMURA, TOMINORI NOMURA, *Sanshin Mfg. Co., Ltd* HIROTAKA TOYODA, *Nagoya University, Plasma Nanotechnology Research Center* Plasmas production in the vicinity of gas-liquid interface is expected as a new liquid treatment technique due to its high production rate of chemically reactive species (OH, O, etc.) and fast transfer of reactive species in liquid phase. So far, we have proposed a microwave plasma device using Venturi effect to treat a liquid, and have reported drastically-enhanced processing performance of organic decomposition by this plasma source. In this study, decomposition performance of various organic compounds such as phenol, methylene blue or diethylenetriamine is investigated. In the experiment, plasma is produced inside a gap between top and bottom parts of the nozzle by a pulsed 2.45 GHz microwave (peak power: <1.2 W, pulse repetition frequency: 10 kHz). During the plasma treatment, solutions are continuously supplied to the nozzle at a flow speed of $10.5 \sim 22.0$ m/s. After the treatment, residual concentration is evaluated by high performance liquid chromatography, gas chromatography and so on. The result indicates the decomposition efficiency becomes different depending on organic matters. Origin of the efficiency difference will be discussed.

LW1 94 Simulation of Nanosecond Pulsed Discharge in Atmospheric Pressure Neon - Comparison between Metal Electrode and Liquid Electrode - KAZUKI MOTOJIMA, NAOKI SHIRAI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* We carried out numerical simulation of nanosecond pulsed discharge in atmospheric pressure neon by two dimensional fluid model. The nanosecond pulsed discharge is generated using two types of electrode configuration; metal needle to metal plane electrodes and metal needle to liquid electrodes. The gap length between electrodes is 1 mm. In case of liquid cathode a liquid layer of 0.6 mm width is added. We confirmed the time evolution leading to bridging the gas gap from streamer propagation. Streamer has thick diameter. It is considered that streamer shape depends on a high ionization rate of neon, electrode shape, and higher applied voltage of nanosecond pulsed discharge than the breakdown voltage. We show the spatial profile of the electric field strength penetration in the liquid from the streamer. The Electric field in the liquid up to 100 kV/cm, which might induce the conductive current. Since the dielectric relaxation time is longer than the pulse width of the applied voltage, the liquid electrode almost behaves as dielectric. The influence of liquid conductivity on the discharge propagation was investigated from the viewpoint of time constant dominant for determining discharge properties.

LW1 95 Characteristics of Liquid Flow Induced by Atmospheric Pressure DC Glow Discharge with Liquid Electrode* FUMIYOSHI TOCHIKUBO, TAKUYA AOKI, NAOKI SHIRAI, SATOSHI UCHIDA, *Tokyo Metropolitan University* In the application of atmospheric-pressure discharges in contact with liquid, primary reactions are initiated between radicals and liquid molecules at plasma-liquid interface. Since the diffusion in the liquid is very slow, some convective flow is necessary to exchange the chemicals at the plasma-liquid interface for the efficient reactions. In our previous work, we found the appearance of specific downward flow in the liquid just below the dc glow discharge in contact with liquid. This downflow will be effective for exchanging the chemicals at plasma-liquid interface. In this work, we investigated the characteristics of liquid flow induced by atmospheric-pressure dc glow discharge with liquid electrode in detail; the influence of voltage polarity, current amplitude, liquid conductivity, the electrode arrangement, and so on. The spatiotemporal development of liquid flow was visualized by schlieren method, and the temperature distribution was measured using temperature-sensitive liquid crystal particles dispersed in the liquid. The liquid-flow characteristics was reproduced by a fluid simulation considering a downward driving force at liquid surface from plasma. The candidate of the driving force will be the momentum transfer of charged species at the liquid surface.

*This work is partly supported by JSPS KAKENHI Grant Number 15H03584.

LW1 96 Shadowgraph Imaging and Numerical Simulation of Cavitation Bubbles Formed in Pulsed Laser Ablation Plasmas in the Vicinity of the Critical Point of CO_2 HITOSHI MUNEOKA, SHOHEI HIMENO, KEIICHIRO URABE, SVEN STAUSS, MOTOYOSHI BABA, TOHRU SUEMOTO, KAZUO TERASHIMA, *University of Tokyo* The characteristic behavior of cavitation bubbles formed in pulsed laser ablation plasmas in supercritical CO_2 were investigated by shadowgraph imaging and numerical simulations. The time evolution of the cavitation bubbles could be divided into three phases near the critical point: Expansion, Double layer formation, and Contraction. The distribution of the refractive index was estimated from the variation of the direction of the refracted light in the shockwave in the expansion phase. It was suggested that the cause of the reduction of the transmitted light in the outer shell in the double-layer phase was not due to refraction, and the contributions of nanoparticles and clusters generated in supercritical fluids were implied. The characteristics in time evolution of the bubble size in the contraction phase, in particular almost constant position of the interface in a relatively long time, was proposed to be due to zero surface tension by numerical simulations. The results suggest that the properties and fluid structure peculiar to SCF affect the structure of cavitation bubbles.

LW1 97 Attempt to control chemical reactions in liquid induced by atmospheric-pressure DC glow discharge AIHITO NITO, NAOKI SHIRAI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* Nonthermal atmospheric-pressure plasmas in contact with liquid are widely studied aiming variety of plasma applications. DC glow discharge with liquid electrode is an easy method to obtain simple and stable plasma-liquid interface. When we focus attention on liquid-phase reaction, the discharge system is considered as electrolysis with plasma electrode. The plasma electrode will supply electrons and positive ions to the liquid surface in a different way from the conventional metal electrode. We tried to control the liquid phase reaction in plasma-assisted electrolysis by using the pH buffer solution to fix the pH, and by using the ion exchange membrane. The advantage of ion exchange membrane is not only the control of ion migration but the use of different solutions at anode side and cathode side. The controllability of plasma-assisted electrolysis in this work was evaluated from the temporal change of chemical species in liquid such as NO2- and NO3-, and from the metal nanoparticles generation.

LW1 98 Pulsed Picosecond and Nanosecond Discharge Development in Liquids with Various Dielectric Permittivity Constants ANDREY STARIKOVSKIY, MICHAEL SHNEIDER, *Princeton University* The dynamics of pulsed picosecond and nanosecond discharge development in liquid water, ethanol and hexane were investigated experimentally. Three possible mechanisms for the propagation of discharge in liquids play a different role depending on the pulse duration. The first case takes place when a "long" (microsecond) electric pulse applied in a non-conducting fluid: as a result of electrostatic repulsion, the formation of low density channels occurs. Consequently, the discharge propagates through the low-density regions. In the second case, under an "intermediate" (nanosecond) electric pulse conditions, the electrostatic forces support the expansion of nanoscale voids behind the front of the ionization wave; in the wave front the extreme electric field provides a strong negative pressure in the dielectric fluid due to the presence of electrostriction forces, forming the initial micro-voids in the continuous medium. Finally, in the third case, when a "short" (picosecond) electric pulse is utilized, the regions of reduced density cannot form because of the extremely short duration of the applied electric pulse. Ionization in the liquid phase occurs as a result of direct electron impact without undergoing a phase transition, occurring due to the acceleration of electrons by an external electric field comparable to the intra-molecular fields. The discharge propagates with a velocity comparable to the local speed of light.

LW1 99 NEGATIVE ION AND DUST PARTICLE CONTAINING PLASMAS

LW1 100 Nonthermal and positron effects on the dust acoustic surface wave in a semi-bounded multi-component Lorentzian dusty plasma* MYOUNG-JAE LEE, YOUNG-DAE JUNG, *Hanyang University* Nonthermal and positron effects on the dust acoustic surface waves propagating at the interface between a multi-component Lorentzian dusty plasma and a vacuum are investigated. The dispersion relation is kinetically derived by employing the specular reflection boundary condition and the dielectric permittivity for dusty plasma containing positrons. We found that there exist two modes of the dust acoustic surface wave; high- and low-frequency modes. We observe that both H- and L-modes are enhanced by the increase of the pair annihilation rate. However, the effects of positron density are duplex depending on the ratio of annihilated positrons. The effects of nonthermal plasmas are also investigated on the H- and L-modes of dust acoustic surface waves. We found that the nonthermal plasmas suppress the frequencies both H- and L-modes.

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LW1 101 Deposition rate and etching rate due to neutral radicals and dust particles measured using QCMs together with a dust eliminating filter RYU KATAYAMA, KAZUNORI KOGA, DAISUKE YAMASHITA, KUNIHIRO KAMATAKI, HYUNWOONG SEO, *Kyushu University* NAHO ITAGAKI, *Kyushu University, PRESTO Japan Science and Technology Agency* MASAHARU SHIRATANI, *Kyushu University* NAOKO ASHIKAWA, MASAYUKI TOKITANI, SUGURU MASUZAKI, KIYOHIKO NISHIMURA, AKIO SAGARA, *National Institute for Fusion Science* THE LHD EXPERIMENTAL GROUP TEAM We have developed an in-situ method for measuring deposition rate of radicals and dust particles using quartz crystal microbalances (QCMs) together with a dust eliminating filter. The QCMs have three channels of quartz crystals. Channel 1 was used to measure total deposition rate due to radicals and dust particles. Channel 2 was covered with a dust eliminating filter. Channel 3 was covered with a stainless-steel plate. Moreover, all QCMs are covered with a grounded stainless steel mesh for suppressing influx of charged particles. The measurements were conducted in the Large Helical Device in the National Institute for Fusion Science, Japan. Although the deposition measurements during the discharges were difficult, we obtained deposition rate and etching rate by comparing the data before and after each discharge. The frequency difference for channel 1 changes from 0.1 Hz (etching) to -0.5 Hz (deposition), while those for channels 2 and 3 are within a range of ± 0.1 Hz and ± 0.05 Hz, respectively. The QCM method gives information on deposition rate and etching rate due to neutral radicals and dust particles.

LW1 102 Dusty Plasma Physics Facility for the International Space Station JOHN GOREE, *The University of Iowa, Dept. of Physics and Astronomy, Iowa City, IA USA* INSEOB HAHN, *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA USA* The Dusty Plasma Physics Facility (DPPF) is an instrument planned for the International Space Station (ISS). If approved by NASA, JPL will build and operate the facility, and NASA will issue calls for proposals allowing investigators outside JPL to carry out research, public education, and outreach. Microgravity conditions on the ISS will be useful for eliminating two unwanted effects of gravity: sedimentation of dust particles to the bottom of a plasma chamber, and masking weak forces such as the ion drag force that act on dust particles. The DPPF facility is expected to support multiple scientific users. It will have a modular design, with a scientific locker, or insert, that can be exchanged without removing the entire facility. The first insert will use a parallel-plate radio-frequency discharge, polymer microspheres, and high-speed video cameras. This first insert will be designed for fundamental physics experiments. Possible future inserts could be designed for other purposes, such as engineering applications, and experimental simulations of astrophysical or geophysical conditions. The design of the facility will allow remote operation from ground-based laboratories, using telescience.

LW1 103 Perpendicular diffusion of a dilute beam of charged particles in the PK-4 dusty plasma* BIN LIU, JOHN GOREE, *Univ. of Iowa, Dept. of Physics and Astronomy, Iowa City, IA USA* We study the random walk of a dilute beam of projectile dust particles that drift through a target dusty plasma. This random walk is a diffusion that occurs mainly due to Coulomb collisions with target particles that have a different size. In the direction parallel to the drift, projectiles exhibit mobility-limited motion with a constant average velocity. We use a 3D molecular dynamics (MD) simulation of the dust particle motion to determine the diffusion and mobility coefficients for the dilute beam. The dust particles are assumed to interact with a shielded Coulomb repulsion. They also experience gas drag. The beam particles are driven by a prescribed net force that is not applied to the target particles; in the experiments this net force is due to an imbalance of the electric and ion drag forces. This simulation is motivated by microgravity experiments, with the expectation that the scattering of projectiles studied here will be observed in upcoming PK-4 experiments on the International Space Station.

*Supported by NASA and DOE.

[1]Bin Liu and J. Goree, Phys. Plasmas **21**, 063704 (2014).

LW1 104 Laser trapped single fine particle as a probe of plasma parameters DAISUKE YAMASHITA, MASAHIRO SOEJIMA, TEPPEI ITO, HYUNWOONG SEO, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* Here we report evaluation of electron density and temperature using optically trapped single fine particle. Experiments were carried out with a radio frequency low pressure plasma reactor, where we set two quartz windows as top and bottom flanges to irradiate an infrared laser light of 1064 nm wavelength from the bottom side [1]. Ar plasmas were generated between a powered ring-electrode set at the bottom of the reactor and a grounded mesh placed at the center of the reactor at 100 Pa by applying 13.56 MHz voltage. The particles injected into the plasmas were monodisperse methyl methacrylate-polymer spheres of 10 μm in diameter. A negatively charged particle, which is suspended plasma sheath boundary, was trapped at the focal point of the irradiated laser light due to the transfer of momentum from the scattering of incident photons. At the beginning of the trapping, particle of 10 μm in size was trapped above 505 μm from the bottom window. After 230 min, the size and position were 9.56 μm and 520 μm, respectively. From the results, the electron density and temperature are deduced to be 1.7×10^9 cm^{-3} and 1.9 eV.

[1]T. Ito *et al.*, J. Phys.: Conf. Ser. **518**, 012014 (2014).

LW1 105 Effect of energetic electrons for dust charging in a large rectangular RF helium plasma SOONGOOK CHO, *Hanyang University* TAEHYEOP LHO, *Plasma Technology Research Center, National Fusion Research Insititute* KYU-SUN CHUNG, *Hanyang University* HANYANG UNIVERSITY COLLABORATION, PLASMA TECHNOLOGY RESEARCH CENTER COLLABORATION A large rectangular RF plasma device ($44 \times 50 \times 120$ cm^3) has been developed for the study of transport and removal of dusts. Effects of dust grains and properties of background plasma are investigated by a planar electric probe in dusty plasma, which is consisted of helium plasma and tungsten dust. To check effect of the energetic electrons on the charging process, low density energetic electrons are produced by applying negative bias to a meshed tungsten grid installed between the upper power electrodes of RF antenna and the bottom ground electrodes. Density and charge of dusts are deduced by comparing pure helium plasma to that of dusty helium plasma.

LW1 106 Development of cesium-free negative hydrogen ion source by using sheet plasma TAKUYA HASE, TAKAAKI IIJIMA, YUTA TANAKA, TOSIKIO TAKIMOTO, AKIRA TONEGAWA, KOHNOSUKE SATO, KAZUTAKA KAWAMURA, *Department of physics, school of science, Tokai University* We demonstrated the production of hydrogen negative ions in cesium-free discharge by using the magnetized sheet plasma. Plasma crossed with a vertical gas flow system and extracting H^- beams from the sheet plasma. Under a secondary hydrogen gas entering the hydrogen plasma, the peak position of the hydrogen plasma is localized in the periphery of the sheet plasma. The maximum negative ion beam is successfully extracted using grids located in the periphery of the sheet plasma. The extraction current density is about 8 mA/cm^2 at extraction voltage is 2 kV and discharge current of 30 A. The extraction negative ion current density is saturated at the extraction voltage is 2 kV for the limit of the negative ion density in the periphery region of the sheet plasma. On the other hand, the extraction current is saturated (3 mA/cm^2) with increasing extraction voltage and the negative ions are not detected without the secondary gas flow (0 sccm). This curve depends on the electrons present. Therefore, it is considered that the negative ion current against the extraction current is around 60% from the ratio of the extraction current and the extraction electron current.

LW1 107 OTHER PLASMA SCIENCE TOPICS

LW1 108 Research on OH(A) Production Mechanism of an Atmospheric He-Water Plasma Jet JINGJING LIU, XIAO HU, *Dept of Mechanical and Electrical Engineering, Guangzhou University* Hydroxyl radicals produced by atmospheric liquid containing plasmas play important role on bacteria killing and wound healing. A He-H_2O plasma jet can produce abundant OH radicals with low gas temperature. At present, some possible reactions to produce OH(A) are concluded, however, the main mechanism to produce OH(A) and the influence of plasma working mode and water vapor concentration on OH(A) generation are still not clear. It is generally regarded that the accurate measurements of electron density and electron temperature play key role on the analysis of OH production mechanism. In this paper, the main generation and loss mechanisms of OH(A) will be found out by both experimental measurements of time-spatial distribution of OH(A) emission intensity, electron density and electron temperature and neutral gas/plasma fluid simulation at different working modes and water vapor concentrations. The influence of plasma working mode and water vapor concentration on OH(A) production and its flux arriving on the substrate is also investigated to optimize the He-H_2O plasma jet for bio-medical application.

LW1 109 The study of data collection method for the plasma properties collection and evaluation system from web JUNHYOUNG PARK, MI-YOUNG SONG, *National Fusion Research Institute* PLASMA FUNDAMENTAL TECHNOLOGY RESEARCH TEAM Plasma databases are necessarily required to compute the plasma parameters and high reliable databases are closely related with accuracy enhancement of simulations. Therefore, a major concern of plasma properties collection and evaluation system is to create a sustainable and useful research environment for plasma data. The system has a commitment to provide not only numerical data but also bibliographic data (including DOI information). Originally, our collection data methods were done by manual data search. In some cases, it took a long time to find data. We will be find data more automatically and quickly than legacy methods by crawling or search engine such as Lucene.

LW1 110 Study of Pulsed vs. RF Plasma Properties for Surface Processing Applications RICKY TANG, MATTHEW HOPKINS, EDWARD BARNAT, *Sandia National Laboratories* PAUL MILLER, *Retired* The ability to manipulate the plasma parameters (density, E/N) was previously demonstrated using a double-pulsed column discharge. Experiments extending this to large-surface plasmas of interest to the plasma processing community were conducted. Differences between an audio-frequency pulsed plasma and a radio-frequency (rf) discharge, both prevalent in plasma processing applications, were studied. Optical emission spectroscopy shows higher-intensity emission in the UV/visible range for the pulsed plasma comparing to the rf plasma at comparable powers. Data suggest that the electron energy is higher for the pulsed plasma leading to higher ionization, resulting in increased ion density and ion flux. Diode laser absorption measurements of the concentration of the 1S5 metastable and 1S4 resonance states of argon (correlated with the plasma E/N) provide comparisons between the excitation/ionization states of the two plasmas. Preliminary modeling efforts suggest that the low-frequency polarity switch causes a much more abrupt potential variation to support interesting transport phenomena, generating a "wave" of higher temperature electrons leading to more ionization, as well as "sheath capture" of a higher density bolus of ions that are then accelerated during polarity switch.

LW1 111 PLASMA ION IMPLANTATION

LW1 112 Low-energy Plasma Ion Implantation NORIYUKI SAKUDO, NORIAKI IKENAGA, KEI MATSUI, *Kanazawa Institute of Technology* We formerly showed that deposited film of NiTi can be crystallized at very low substrate temperature without any post-annealing treatment by using simultaneous ion irradiation with sputter deposition. Since the ion energy for optimum crystallization was around 80 eV which was very low compared with usual plasma ion implantation, the ion acceleration voltage was determined by the potential difference between the pulse bias voltage which was negative and the plasma potential which was positive with respect to the grounded chamber. In this study we find that the plasma potential itself changes as functions of the bias voltage as well as the configuration factor, i.e., the area ratio of the bias electrode surface to the chamber wall surface. In order to get the exact ion energy we obtain a new formula for plasma potential by deducing from the equation for continuity of charged-particle currents in plasma. Resultantly, it is shown that the plasma potential differs from that obtained by the conventional simple plasma model, especially when the electron temperature and/or the configuration factor become higher. In some cases the bias voltage might be positive in order to keep the ion energy as low as around 80 eV.

LW1 113 Ion extraction optics with tunable ion angular distribution of ribbon beams COSTEL BILOIU, DANIEL DISTASO, CHRISTOPHER CAMPBELL, VIKRAM SINGH, ANTHONY RENAU, *Applied Materials, Silicon Systems Group, Varian Semiconductor Equipment* The characteristics of the ion angular distribution (IAD) of an extracted ion beam are determined by the shape, location, and orientation of the plasma meniscus. We describe an electrostatic lens that allows modification of plasma meniscus topology and as a result in situ control of the IAD of extracted ribbon ion beams, i.e., control of ion mean angle and angular spread. The ion extraction optics supposes the use of an electrode immersed in the plasma which is located adjacent to the extraction slit. By electrically biasing the electrode relative to the plasma, the meniscus topology and its orientation relative to the wafer plane can be controlled. Thus, 300 mm wide ribbon ion beams with characteristic mean angle spanning from 0° to 50° and angular spread as low as 4° can be obtained. Ion angular distribution can be tuned in terms of mean angle and angular spread for different ion beam energies and beam currents. In addition, being made of conductive material, the extraction optics is insensitive to the possible conductive deposits resulting from byproducts of ion beam bombardment of the wafer surface.

LW1 114 Adjustable, High Voltage Pulse Generator with Isolated Output for Plasma Processing* TIMOTHY ZIEMBA, KENNETH E. MILLER, JAMES PRAGER, ILIA SLOBODOV, *Eagle Harbor Technologies, Inc.* Eagle Harbor Technologies (EHT), Inc. has developed a high voltage pulse generator with isolated output for etch, sputtering, and ion implantation applications within the materials science and semiconductor processing communities. The output parameters are independently user adjustable: output voltage (0 – 2.5 kV), pulse repetition frequency (0 – 100 kHz), and duty cycle (0 – 100%). The pulser can drive loads down to 200 Ω. Higher voltage pulsers have also been tested. The isolated output allows the pulse generator to be connected to loads that need to be biased. These pulser generators take advantage modern silicon carbide (SiC) MOSFETs. These new solid-state switches decrease the switching and conduction losses while allowing for higher switching frequency capabilities. This pulse generator has applications for RF plasma heating; inductive and arc plasma sources; magnetron driving; and generation of arbitrary pulses at high voltage, high current, and high pulse repetition frequency.

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LW1 115 GREEN PLASMA TECHNOLOGIES: ENVIRONMENTAL AND ENERGY APPLICATIONS

LW1 116 Photocatalytic characterization of oxygen vacancy TiO_2 prepared with Ar/H_2 plasma surface treatment* TAKUMA NAKANO, SUMIO KOGOSHI, NOBORU KATAYAMA, *Tokyo University of Science* It has been observed that oxygen vacancy TiO_2 (TiO_{2-x}) prepared with Ar/H2 plasma surface treatment have an optimal process condition for visible light photocatalytic activity. However it may depend on the plasma process system. Therefore, it is desirable to describe the optimal condition with a more general term, for example the x value of TiO_{2-x}. In addition the reason why the optimal condition exists is unclear. In this study, we carried out the measurement to find out the dependence of visible light photocatalytic activity on the x value and ab initio calculation of density of states (DOS) of TiO_{2-x}. The dependence of visible light photocatalytic activity of TiO_{2-x} on the x value has been estimated experimentally. When the x value was 0.069, the visible light photocatalytic activity was optimal. The results of the calculation have suggested a new oxygen vacancy state would emerge at a nearly center between the valence band and the conduction band for larger x values. This result implies that the recombination rate between electrons and holes would increase, resulting in less photocatalytic activity for the larger x value.

*This work was partially supported by a JSPS KAKENHI Grant Number 25340073.

LW1 117 Optical Engines, Organic Spintronics & Ice-Cube/Astranomcs Notions* FATAHILLAH HIDAJATULLAH-MAKSOED,[†] *PT. INDONESIAN Goodrich-PINDAD Aeronautical Systems* FAUZAN FAIZAL-IMADUDDIN, *Department of Industrial Engineering, UNIVERSITY OF WIDYATAMA, Bandung-40115, INDONESIA* Refers to "Optical engines for light energy detection," PhysicsToday,June 2012, h 60 denotes NewPortCorp's OptoFlash is a miniature multichannel spectrometer engine that detects lght energy at multiple wavelengths. According to NewPort, the demultiplexing optical engine is easy to customize. Involves the Computational Fluid Dynamics/ContractForDifferences, there were sought for "LaserDopplerVelocimetry/LDV, we intended to comprises the lVDT include in Sensor technology as well as to PVDF/polyvynilidine fluoride who comprises giant flexoelectric in alpha-phase-Xiaoning Jiang *et al.*"Flexoelectric Nanogenerator:Materials, structures & devices," 2013 paved with good intentions, the "jellium model" [Overhauser, 1963a] maybe can be interrelated to reflex action & primary process used by Id to avoids pain in painstakingly to wieghs spin relaxation & dephasing process that guides "EQILIBRATION." Also offered the spintronics using PID-controller, from Microbisl Cells to "The Motor Response inPlasma Heating." Further, the Aug 1985 FAA Certification for IAI 1125 ASTRA Jet Corp inherently existed between Julian C. Blecker's dissertation to "realistic mathematics" from Prof. R.K. Sembiring/MA-ITB.

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[†]Herewith avoiding risk of installation-misunderstands through Avazur, Inc provided by HE. Mr. BrigadierGeneral-TNI[rtd] H. Ing. Tb. A. ZOEHRI.

LW1 118 Reforming of biogas to synthesis gas by a rotating arc plasma at atmospheric pressure WOO-JAE CHUNG, HYUN-WOO PARK, JING-LIN LIU, DONG-WHA PARK, *Department of Chemistry and Chemical Engineering, Inha University* In order to produce synthesis gas, reforming of biogas composed with 60 percent for CH4 and 40 percent for CO2 was performed by a novel rotating arc plasma process. The effect of O2/CH4 ratio on the conversion, syngas composition and energy cost was investigated to evaluate the performance of proposed system compared with conventional gliding arc plasma process. When the O2/CH4 ratio was increased from 0.4 to 0.9, the conversions of CH4 and O2 increased up to 97.5 percent and 98.8 percent, respectively, while CO2 conversion was almost constant to be 38.6 percent. This is due to more enhance the partial oxidation of CH4 to CO and H2 than that of dry reforming by increasing the O2/CH4 ratio. In this work, energy cost of 32 kJ/mol was achieved with high syngas composition of 71 percent using pure O2 as oxidant reactant. These are lower than those of different arc plasma processes (energy cost of 122 - 1870 kJ/mol) such as spark, spark-shade and gliding arc plasma. Because, this rotating arc plasma can remain in a long arc length and a large volume of plasma with constant arc length mode.

LW1 119 Conversion of CO_2 to CH_4 by a coaxial hydrogen plasma shower method SATORU IIZUKA, KEISUKE ARITA, *Graduate School of Engineering, Tohoku University* Conversion of CO_2 to CH_4 was investigated by using a coaxial hydrogen plasma shower method. Hydrogen radicals produced by hydrogen plasma in an inner tube were ejected through a narrow channel between a core rod electrode and the inner tube toward downstream reaction region, where carbon dioxide was supplied from an outer tube. Conversion rate of CO_2 to CH_4 was investigated by changing the discharge parameters such as applied voltage, gas flow rate, and so on. Carbon dioxide was successively reduced by hydrogen radicals. Maximum conversion rate of about 50% was established. This system provided very efficient conversion of CO_2 to CH_4.

LW1 120 Influence of Sodium Carbonate on Decomposition of Formic Acid by Discharge inside Bubble in Water MASASHI IWABUCHI, KATSUYUKI TAKAHASHI, KOICHI TAKAKI, NAOYA SATTA, *Iwate University* An influence of sodium carbonate on decomposition of formic acid by discharge inside bubble in water was investigated. Oxygen or argon gases were injected into the water through a vertically positioned glass tube, in which the high-voltage wire electrode was placed to generate plasmas at low applied voltage. The concentration of formic acid was determined by ion chromatography. In the case of addition of sodium carbonate, the pH value increased with decomposition of the formic acid. In the case of oxygen injection, the increase of pH value contributed to improve an efficiency of the formic acid decomposition because the reaction rate of ozone and formic acid increased with increasing pH value. In the case of argon injection, the decomposition rate was not affected by the pH value owing to the high rate constants for loss of hydroxyl radicals.

LW1 121 A Compact Plasma Flow-Bubbler for Decomposition of Organic compounds and Sterilization HIROYUKI YOSHIKI, FUKUTO ISHIKAWA, YU IGARASHI, *Tsuruoka National College of Technology* TETUYA SUGAWARA, *Yamagata Research Institute of Technology* Recently, Plasma production in and in contact with liquid has attracted much attention because of their applications to degradation of organic compounds, sterilization, water purification. UV, electron, ion and radical flows originated from a plasma and also shock wave induce physical and chemical reaction in a liquid, for example oxidation-reduction, electrolysis and reactive species production in a water. In particular, various reactive oxygen/nitrogen species generated at the plasma-liquid interface play an important role in oxidation and degradation of organic pollutants and bacteria. We have proposed the mild water treatment by ejecting the atmospheric-pressure μ plasma (APμP) flow into a water using a microbubble aerator or a porous ceramics bubbler. In this study, a compact plasma flow-bubbler made up of a μplasma source and a porous ceramics has been developed for the applications of water purification and sterilization. APμP is generated between a thin metal pipe electrode and a GND plate by a pulsed high voltage, so that the O_2 μ plasma can be obtained without adding He and Ar gases. Plasma flow is ejected into the water through a porous ceramics. Decolorization of an indigo carmine solution strongly depended on O_2 flow rate. Chemical probe method using terephthalic acid revealed that OH radicals are produced by the O_2 plasma gas bubbling. The inactivation for *E. coli*, *Bacillus subtilis* was attained by the O_2 plasma gas bubbling.

LW1 122 CH_4-CO_2 reforming in surface DBD reactor with ZnO-Cu and NiO catalysts* CLAUDIA LAZZARONI, ABDELKADER RAHMANI, MEHRDAD NIKRAVECH, *LSPM-CNRS, Institut Galilée, Université Sorbonne Paris Cité, Université Paris 13* MP4 TEAM Dry reforming of methane (CH_4) is carried out in an atmospheric pressure Dielectric Barrier Discharge (DBD) reactor. The two 3 mm thickness aluminum electrodes are separated by a 3 mm thickness dielectric sheet made of quartz. The electrodes present 3 branches and the space between two adjacent branches is filled with beads of catalyst which are 2 mm diameter alumina beads coated with ZnO-Cu or NiO. The coating is performed in two different ways: (i) by impregnation and (ii) by fluidized spray plasma. A 30 kHz and several kV AC voltage is applied to the electrodes. The feedstock gas is a mixture of argon, carbon dioxide (CO_2) and methane with individual fluxes varying from 20 to 80 mL/min. At the reactor outlet, the gas goes through a condenser at 4°C to condense liquid products. The reforming reaction products are identified by liquid and gas phase chromatography. The effect of the applied power and the catalyst nature on the product distribution is studied. Whatever the catalyst, the conversion rate of CH_4 and CO_2 increases with the applied power while the selectivity of gas products is almost independent of the power. The condensed liquids collected under our experimental conditions, such as ethanol or acetic acid, represent more than 10% of the products.

*This work is partially supported by the Programme Interdisciplinaire SPC: Énergie, Société, Territoire.

LW1 123 Generation of pulsed discharge plasma in water with fine bubbles YUI HAYASHI, NORIHARU TAKADA, HIDEKI KANDA, MOTONOBU GOTO, *Nagoya University* GOTO LABORATORY TEAM Recently, some researchers have proposed electric discharge methods with bubbles in water because the discharge plasma inside bubble was easy to be generated compared to that in water. Almost all of these methods introduced bubbles in the order of millimeter size from a nozzle placed in water. In these methods, bubbles rose one after another owing to high rising speed of millibubble, leading to inefficient gas consumption. We proposed fine bubbles introduction at the discharge area in water. A fine bubble is determined a bubble with less than 100 μm in a diameter. Fine bubbles exhibit extremely slow rising speed. Fine bubbles decrease in size during bubble rising and subsequently collapse in water with OH radical generation. Therefore, combining the discharge plasma with fine bubbles is expected to generate more active species with small amount of gas consumption. In this work, fine bubbles were introduced in water and pulsed discharge plasma was generated between two cylindrical electrodes which placed in water. We examined effects of fine bubbles on electric discharge in water when argon or oxygen gas was utilized as feed gas. Fine bubbles enhanced optical emission of hydrogen and oxygen atoms from H_2O molecules, but that of feed gas was not observed. The formation mechanism of H_2O_2 by electric discharge was supposed to be different from that with no bubbling. Dissolved oxygen in water played a role in H_2O_2 formation by the discharge with fine bubbles.

LW1 124 Enhancement of burning velocity by dissociated oxygen atoms* HARUAKI AKASHI, TOMOKAZU YOSHINAGA, *Dept. Appl.Phys., National Defense Academy, Japan* KOICHI SASAKI, *Div. Quantum Sci. Eng., Hokkaido University* Green technology, such as preventing global warming, has been developed for years. Researches on plasma assisted combustion is one of the technologies and have been done for investigating more efficient combustion, more efficient use of fossil fuel with plasmas or applying electric fields. In the ignition time delay analyses with the dissociated oxygen atoms which is generated by non-equilibrium plasma had significant effect on the ignition time. In this paper, dissociated oxygen could effect on burning velocity or not has been examined using CHEMKIN. As a result, no effect can be seen with dissociation degree of lower than 10^{-3}. But there is an effect on the enhancement of burning velocity with higher degree of 10^{-3}. At the dissociation degree of 5×10^{-2}, the burning velocity is enhanced at a factor of 1.24. And it is found that the distributions of each species in front of preheat zone are completely different. The combustion process is proceeded several steps in advance, and generation of H_2O, CO and CO_2 can be seen before combustion in higher dissociation case.

*This work was supported by KAKENHI (22340170).

LW1 125 Evaluation of Applied Magnetic Field on Reduction Efficiency of Alumina Powder SATO YUSUKE, RYO MYOEN, MAKOTO MATSUI, *Shizuoka University* KIMIYA KOMURASAKI, YOSHIHIRO ARAKAWA, *University of Tokyo* Alumina reduction method using laser sustained plasma (LSP) is proposed for energy storage system using aluminum. In our previous study, the averaged reduction efficiency in the plasma was estimated as five percent. Aluminum has property which is easily oxidized. Therefore, active separation of oxygen and aluminum is important for enhancement of collection efficiency. In this research, Al ion is separate from oxygen by applying magnetic field.

LW1 126 Production of composite Si nanoparticles by plasma spraying PVD and CH_4 annealing for negative electrodes of lithium ion batteries* RYOSHI OHTA, YUTARO OHTA, TORU TASHIRO, MAKOTO KAMBARA, *The University of Tokyo* Si is a promising candidate as anode of next generation high density Li ion batteries. This material, however, needs to be nanostructured, nanoparticles and C coating of active material, to cope with huge volume change and associated rapid capacity decay. Si nanoparticles with 20–40 nm have been successfully produced by plasma spraying PVD and also Si-C core-shell composite particles by adding CH_4 during processing. The battery performance has been improved with these nanopowders as anode, especially with the C coated Si particles. However, SiC that is inactive in battery reaction forms inevitably at high temperature during plasma spraying PVD and reduces the capacity density. In this work, therefore, post CH_4 annealing was attempted to form Si-C nanocomposite particles while suppressing formation of SiC. The primary Si nanoparticles were unchanged in size after annealing and were coated with the finer carbonous particles that formed after CH_4 infiltration through pores between nanoparticles. The batteries using annealed powders with C/Si molar ratio of 0.3 have shown two-fold capacity retention increase after 50 cycles with no capacity reduction associated with SiC formation as compared to the powders without C.

*This work was partly supported by the Funding Program for Next Generation World-Leading Researchers (NEXT Program) of Japan.

LW1 127 Dielectric Barrier Discharge Methane Conversion CHONG LIU, ALEXANDER FRIDMAN, ALEXANDER RABINOVICH, DANIL DOBRYNIN, *Drexel plasma institute, Drexel university* With the large amount of nature gas discovery every year, there is an increasing interest on modification of methane. The

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fact that methane is gaseous makes it less economic and efficient than liquid fuel. Here we propose a new way of converting methane from gas phase to liquid phase. Dielectric barrier discharge is used to treat methane and nitrogen mixture bubbles inside of liquid fuel. Nitrogen is here to help activate methane into an excited state, then it is possible for the excited molecules to react with other liquid hydrocarbon. Gaseous methane is converted in to liquid phase when excited methane replace a hydrogen and add onto the carbon chain. In this study some preliminary experiments is done to verify this hypothesis. There is equivalent weight increases with methane and nitrogen mixture discharging in diesel when compare to only nitrogen discharging in diesel. The same experiment have also been done with gas mixture discharged in 1-methylnaphthalene. And FTIR analysis of the after treatment hydrocarbon liquid all indicates that there is an increasing in C-H bond concentration and a decreasing in phenyl ring structure.

LW1 128 PLASMA PROCESSING FOR PHOTOVOLTAIC APPLICATIONS

LW1 129 Effects of electrode structure on characteristics of multi-hollow discharges* YOSHIHIRO TORIGOE, KIMITAKA KEYA, SUSUMU TOKO, HYUNWOONG SEO, HAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, *Faculty of Information Science and Electrical Engineering, Kyushu University* Silane plasmas are widely employed for hydrogenated amorphous silicon (a-Si:H) film deposition. Amorphous silicon nanoparticles below 10 nm in size (clusters) are formed in silane plasmas and some of them are incorporated into a-Si:H films, leading to the light induced degradation which is the most important issue for a-Si:H solar cells. To suppress cluster incorporation, a multi-hollow discharge plasma CVD method has been developed and succeeded in depositing highly stable a-Si:H films. For further improvement of the film qualities, we have employed a thicker grounded electrode to suppress plasma expansion toward the deposition region. From optical images of the discharge plasmas, the expansion was significantly suppressed using 10 mm thick grounded electrode. For the 10 mm thick electrode, optical emission intensity ratio of Si* (288 nm) and SiH* (414 nm) I_{Si*}/I_{SiH*}, which shows a ratio of cluster generation ratio and radical ones, was 20% of that for 1mm thick electrode. These results suggest that the generation of clusters was also suppressed using the 10 mm thick grounded electrode.

*This study was partly supported by NEDO and PVTEC.

LW1 130 Investigation the cause of plasma treatment for low temperature annealed dye-sensitized solar cells* SHUNGO ZEN, YUTA KOMATSU, RYO ONO, *The University of Tokyo* Dye-sensitized solar cells (DSSCs) require annealing of TiO_2 photoelectrodes at 450 C to 550 C. However, such high-temperature annealing is unfavorable because it limits the use of materials that cannot withstand high temperatures, such as plastic substrates. In our previous paper, a low temperature annealing technique of TiO_2 photoelectrodes using ultraviolet light and dielectric barrier discharge treatments was proposed to reduce the annealing temperature from 450 C to 150 C for a TiO_2 paste containing an organic binder. Here, we investigated the cause of plasma treatment via the Nyquist diagram (Cole-Cole plot) of DSSCs. The Nyquist diagram was masured with a frequency response analyzer (NF Corporation, FRA5022) under 100 mW/cm^2 illumination of a calibrated xenon lamp (Hamamatsu L2274, 150W). The lifetime of the electrons, the effective electron diffusion coefficient, and the electron diffusion length of TiO_2 photoelectrodes were determined by analyzing the Nyquist diagrams. As a result of analyzing the Nyquist diagrams, it was shown that plasma treatment can reduce the electron transport resistance and promote the necking of Hot UV annealed TiO_2 nanoparticles.

*This work was supported by Grant-in-Aid for JSPS Fellows.

LW1 131 Ratio of Cu, Zn, Sn and S densities in magnetron sputtering plasmas employing a stoichiometric Cu_2ZnSnS_4 target NAYAN NAFARIZAL, *Hokkaido University & Universiti Tun Hussein Onn Malaysia* KOICHI SASAKI, *Hokkaido University* Recently, Cu_2ZnSnS_4 (CZTS) has drawn wide attention as a highly potential material for the next-generation thin film solar cells. In order to optimize CZTS thin films for solar cells, it is essential to understand their deposition mechanism. Especially since it consists of four elements, it is difficult to control the stoichiometric properties. In the present work, we measured the absolute ground-state densities of Cu, Zn, Sn, and S atoms released from a stoichiometric CZTS target in magnetron sputtering plasmas. The absolute atom densities were evaluated by ultraviolet and vacuum ultraviolet absorption spectroscopy. Magnetron sputtering plasmas were produced using a pulsed-modulated rf power supply and the temporal variations of atom densities were measured in the afterglow. The absolute Cu, Zn, Sn and S densities in the discharge phase were evaluated by the extrapolations of the temporal variations. It has been observed that the absolute Cu, Zn, Sn and S densities in the gas phase were not in agreement with the stoichiometry of the target as well as that of the deposited film. The results suggest possibilities of unconventional sputtering and deposition processes in the compound sputter deposition.

LW1 132 Raman spectroscopy of PIN hydrogenated amorphous silicon solar cells KIMITAKA KEYA, YOSHIHIRO TORIGOE, SUSUMU TOKO, DAISUKE YAMASHITA, HYUNWOONG SEO, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* Light-induced degradation of hydrogenated amorphous silicon (a-Si:H) is a key issue for enhancing competitiveness in solar cell market. A-Si:H films with a lower density of Si-H_2 bonds shows higher stability [1]. Here we identified Si-H_2 bonds in PIN a-Si:H solar cells fabricated by plasma CVD using Raman spectroscopy. A-Si:H solar cell has a structure of B-doped μc-SiC:H (12.5 nm)/ non-doped a-Si:H (250nm)/ P-doped μc-Si:H (40 nm) on glass substrates (Asahi-VU). By irradiating HeNe laser light from N-layer, peaks correspond to Si-H_2 bonds (2100 cm^{-1}) and Si-H bonds (2000 cm^{-1}) have been identified in Raman scattering spectra. The intensity ratio of Si-H_2 and Si-H I_{SiH2}/I_{SiH} is found to correlate well to light induced degradation of the cells Therefore, Raman spectroscopy is a promising method for studying origin of light-induced degradation of PIN solar cells.

[1]T. Nishimoto *et al.*, J. Non-Crystal. Solids **299-302**, 1116 (2002).

LW1 133 Effects of N_2 dilution on fabrication of Ge nanoparticles by rf sputtering SHNJI HASHIMOTO, SOUTA TANAMI, HYUNWOONG SEO, *Kyushu University* GIICHIRO UCHIDA, *Osaka University* DAISUKE YAMASHITA, KUNIHIRO KAMATAKI, NAHO ITAGAKI, KAZUNORI KOGA, MASHARU SHIRATANI, *Kyushu University* Multiple exciton generation (MEG) in QDs is expected to enhance significantly the energy conversion efficiency of solar cells. Although there are several reports on MEG characteristics from various QD materials such as PbS, CdSe, CdS ZnS, and Ag_2S, such materials have disadvantages of their toxicity and limited resources. Here we have developed quantum-dots (QDs) solar cells using Ge nanoparticles fabricated by rf sputtering method under high pressure. We fabricated Ge nanoparticles by rf sputtering at a pressure of 1.5 Torr. Since the mean free path of Ge atoms is an order of micrometer, and Ge nanoparticles are formed in gas phase. We fabricated Ge nanoparticles using Ar and N_2 to terminate surface defects by N. Ge and Ar emission intensities decrease significantly with increasing N_2 partial pressure. The electron density was measured with a plasma absorption probe. The electron density decreases with increasing N_2 partial pressure.

LW1 134 Femtosecond Laser Processing Characterization of Organic Thin Film NORIO TSUDA, YUKI MAKINO, JUN YAMADA, *Aichi Institute of Technology* Laser processing characterization of organic thin film solar cell is important for solar cell production technique. Femtosecond laser is able to process low thermal damage processing. Laser processed surface of organic thin film is checked and the processing characterization is investigated.

LW1 135 BIOLOGICAL APPLICATIONS OF PLASMAS

LW1 136 Effects of Ambient Humidity on Plant Growth Enhancement by Atmospheric Air Plasma Irradiation to Plant Seeds THAPANUT SARINONT, TAKAAKI AMANO, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* Humidity is an important factor for plasma-bio applications because composition of species generated by atmospheric pressure plasmas significantly depends on the humidity [1]. Here we have examined effects of humidity on the growth enhancement to study the mechanism. Experiments were carried out with a scalable DBD device [2]. 10 seeds of *Raphanus sativus L.* were set for x = 5 mm and y = 3 mm below the electrodes. The humidity H_{air} was 10 - 90 %Rh. The ratio of length of plants with plasma irradiation to that of control increases from 1.2 for H_{air} = 10 %Rh to 2.5 for H_{air} = 50 %Rh. The ratio is 2.5 for H_{air} = 50-90 %Rh. This humidity dependence is similar to the humidity dependence of O_2^+-H_2O, H_3O^*, NO_2^--H_2O and NO_3^--H_2O densities, whereas it is different from that of other species such as O_3, NO, and so on [1]. The similarity gives information on key species for the growth enhancement.

[1]T. Murakami *et al.*, Plasma Sources Sci. Technol. **22**, 015003 (2013).
[2]S. Kitazaki *et al.*, Curr. Appl. Phys. **14**, S149 (2014).

LW1 137 Characterization of Atmospheric Pressure Plasma Jet (APPJ) and Its Effect on Plasmid DNA* EK ADHIKARI, SYLWIA PTASINSKA, *University of Notre Dame, Notre Dame, IN* A helium atmospheric pressure plasma jet (APPJ) source was constructed and then characterized by monitoring a deflected current on a high voltage electrode and a potential difference between two electrodes. The deflected current was also monitored for the APPJ source with varied electrical and fed gas composition e.g. admixtures of He and water vapor. The deflected power per cycle for gas admixtures was decreased with the increase in fraction of water vapor. In addition, this APPJ source was used to induce damage to aqueous plasmid DNA. The fraction of supercoiled, single-strand breaks and double-strand breaks in DNA were quantified by using agarose gel electrophoresis. The number of DNA strand breaks increased as a function of plasma irradiation time and decrease as a distance between APPJ and DNA sample increased. The APPJ with the gas admixture, in which the fraction of water vapor was varied, was also used to induce damage to aqueous DNA samples. The damage level decreased with the increase in a fraction of water vapor under specific experimental conditions. The change in numbers of DNA strand breaks irradiated by a pure He plasma and a plasma with a gas admixture is predicted by different physical and chemical process in the APPJ.

*This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Basic Energy Sciences under Award Number DE-FC02-04ER15533.

LW1 138 Study on the role of active radicals on plasma sterilization inside small diameter flexible polymeric tubes* HIROTO MSTSUURA, TAKATOMO FUJIYAMA, YASUKI OKUNO, MASAKAZU FURUTA, SHUICHI OKUDA, *Osaka Prefecture University* YUICHIRO TAKEMURA, *Kinki University* Recently, atmospheric pressure discharge plasma has gathered attention in various fields. Among them, plasma sterilization with many types of plasma source has studied for decades and its mechanism is still an open question. If active radicals produced in plasma has main contribution of killing bacterias, direct contact of the so-called plasma flame might not be necessary. To confirm this, sterilization inside small diameter flexible polymeric tubes is studied in present work. DBD type plasma jet is produce by flowing helium gas in a glass tube. A long polymeric tube is connected and plasma jet is introduced into it. Plasma flame length depends on helium gas flow rate, but limited to about 10 cm in our experimental condition. E.colis set at the exit plasma source is easily killed during 10 min irradiation. At the tube end (about 20 cm away from plasma source exit), sterilization is possible with 30 min operation. This result shows that active radical is produced with helium plasma and mist contained in sample, and it can be transferred more than 20 cm during it life time. More plasma diagnostic data will also be shown at the conference.

*This work was partially supported by the "ZE Research Program, IAE(ZE27B-4).

LW1 139 Effects of atmospheric pressure non-thermal plasma treatments on aflatoxigenic fungi and its host BO-CHEN CHEN, *Institute of Space And Plasma Science, NCKU* This experiment tests the ability of atmospheric pressure non-thermal plasma treatments in the prevention of fungi infection. There are charged particles, electric field, radicals and UV light inside plasmas and these elements might trigger different physical or chemical effects during non-thermal plasma treatments. In this experiment, the experimental samples received indirect plasma treatments with different time duration and gas compositions which mean only the remote effects caused by plasma treatments could be seen. In this work, plasmas were produced by dielectric barrier discharge method. The operation gases were air and a mixed gas of 97% He and 3%O_2. After plasma treatments, fungi growth rate was observed by taking pictures and the existence of aflatoxin was qualitatively detected by black light method. The final results show that the radicals in both He/O_2 and air plasma might facilitate fungi growth rate which means peanuts received indirect plasma treatments grew fungi faster than control group. The outcomes of aflatoxin detection also shows that the fungi grown on all the sample are aflatoxigenic fungi.

LW1 140 Inactivation of Pathogenic Bacteria on Seeds by Active Oxygen Species Generated in Low-Pressure Plasma REOTO ONO, SHOHEI UCHIDA, NOBUYA HAYASHI, *Kyushu University* RINA KOSAKA, YASUTAKA SOEDA, *Sumika Agrotech Co., Ltd.* The inactivation of bacteria on seeds by active oxygen species generated by a low-pressure oxygen plasma is investigated. Species of active oxygen contributing to the inactivation of bacteria are attempted to be identified. Cylindrical stainless chamber with the internal volume of 17 L is used and RF antenna is set inside the chamber. The oxygen gas pressure is 20–100 Pa. RF power of 13.56 MHz is supplied to RF antenna and CCP is generated. After irradiation, bacteria are extracted from seeds and cultivated on nutrient agars. The number of colonies on these agars is counted after 48 h incubation. The number of bacteria on seeds decreases to less than 10^{-3} after plasma irradiation for 45 min comparing with that of control. The tendency of the reduction rate of bacteria on seeds has positive correlation with that of the light emission intensity of the singlet excited oxygen molecule as the oxygen gas pressure is varied. It is supposed that the singlet excited oxygen molecule would be one of the major factors for the inactivation of bacteria on seeds.

LW1 141 Disinfection effect of non-thermal atmospheric pressure plasma for foodborne bacteria* MOHAMMAD RASEL PERVEZ, TAKANORI INOMATA, TATSUO ISHIJIMA, MAKIKO KAKIKAWA, YOSHIHIKO UESUGI, YASUNORI TANAKA, *Kanazawa University* TOSHIHIRO YANO, *Kanazawa Gakuin Junior College* SHOJI MIWA, *Ishikawa Agriculture and Forestry Research Center* AKINORI NOGUCHI, *Sodick Co., Ltd* Non-thermal atmospheric pressure plasma (NAPP) exposure can be a suitable alternative for bacteria inactivation in food processing industry. Specimen placed in the enclosure are exposed to various reactive radicals produced within the discharge chamber. It is also exposed to the periodic variation of the electric field strength in the chamber. Dielectric barrier discharge is produced by high voltage pulse (V_{pp} = 18 kV, pulse width 20 μs, repetition frequency 10 kHz) in a polypropylene box (volume = 350 cm^3) using helium as main feed gas. Inactivation efficiency of NAPP depends on the duration of NAPP exposure, applied voltage pulse strength and type, pulse duration, electrode separation and feed gas composition. In this study we have investigated inactivation of *Bacillus lichenformis* spore as an example of food borne bacteria. Keeping applied voltage, electrode configuration and total gas flow rate constant, spores are exposed to direct NAPP for different time duration while O_2 concentration in the feed gas composition is varied. 10 minutes NAPP exposure resulted in ~ 3 log reduction of *Bacillus lichenformis* spores for 1% O_2 concentration (initial concentration ~ 10^6 / specimen).

*This work is supported by research and development promotion grant provided by the Hokuriku Industrial Advancement Center.

LW1 142 Mechanism of Growth Enhancement of Plants Induced by Active Species in Plasmas SATOSHI WATANABE, REOTO ONO, NOBUYA HAYASHI, *Kyushu University* Plant growth enhances when seeds are irradiated by plasma. However the mechanism of the growth enhancement by plasma has not been clarified. In this study, growth enhancement of plants using various active species and variation of plant cells are investigated. RF plasma is generated under conditions where pressure is 60 Pa and input electrical power is 60 W. Irradiation period varies from 0 (control) to 75 min. Air plasma shows maximum growth of plants with irradiation period of 60 min on the other hand, oxygen plasma shows the maximum growth with irradiation period of 15 min. From change of gaseous species and pressure dependence, growth enhancing factor is expected to be active oxygen species produced in plasma. According to gene expression analysis of Arabidopsis, there are two speculated mechanism of plant growth enhancement. The first is acceleration of cell cycle by gene expressions of photosynthesis and glycolytic pathway, and the second is increase of cell size via plant hormone production.

LW1 143 Simple Evaluation Method of Atmospheric Plasma Irradiation Dose using pH of Water KAZUNORI KOGA, THAPANUT SARINONT, TAKAAKI AMANO, HYUNWOONG SEO, NAHO ITAGAKI, YOSHIMICHI NAKATSU, AKIYO TANAKA, MASAHARU SHIRATANI, *Kyushu University* Atmospheric discharge plasmas are promising for agricultural productivity improvements and novel medical therapies, because plasma provides high flux of short-lifetime reactive species at low temperature, leading to low damage to living body. For the plasma-bio applications, various kinds of plasma systems are employed, thus common evaluation methods are needed to compare plasma irradiation dose quantitatively among the systems. Here we offer simple evaluation method of plasma irradiation dose using pH of water. Experiments were carried out with a scalable DBD device [1,2]. 300 μl of deionized water was prepared into the quartz 96 microwell plate at 3 mm below electrode. The pH value has been measured just after 10 minutes irradiation. The pH value was evaluated as a function of plasma irradiation dose. Atmospheric air plasma irradiation decreases pH of water with increasing the dose. We also measured concentrations of chemical species such as nitrites, nitrates and H_2O_2. The results indicate our method is promising to evaluate plasma irradiation dose quantitatively.

[1] S. Kitazaki *et al.*, Curr. Appl. Phys. **14**, S149 (2014).
[2] S. Kitazaki *et al.*, MRS Proc. **1469** (2012) mrss12-1469-ww0608.

LW1 144 Viability preserved capture of microorganism by plasma functionalized carbon-encapsulated iron nanoparticles* ANCHU VISWAN, *GSST, Shizuoka University, Hamamatsu, Japan* KUNIAKI SUGIURA, *Graduate School of Engineering, Shizuoka University, Hamamatsu, Japan* MASAAKI NAGATSU, *GSST and Graduate School of Engineering, Shizuoka University, Hamamatsu, Japan* Carbon-encapsulated iron nanoparticles (Fe@C NPs) were synthesized by DC arc discharge method. Carbon encapsulation makes the particles hydrophobic, however for most of the biomedical applications they need to be hydrophilic. To attain this, the particles were amino functionalized by RF plasma. Effect of gas mixture ratio (Ar/NH_3), pretreatment, post-treatment times and RF power were optimized. By varying the RF plasma conditions, the amino group population on the surface of Fe@C NPs were increased. With conventional chemical method the amino group population on particles, synthesized in different conditions was found to be ranging from 3-7 × 10^4 per particle. Bioconjugation efficiency of the nanoparticles was examined by biotin-avidin system, which can be simulated for antigen-antibody reactions. Results from the UV absorption and fluorescence spectroscopy shows increment in bioconjugation efficiency, with the increase of amino group population on the nanoparticles. After confirming the bioconjugation efficiency, the amino functionalized Fe@C NPs were modified with antibodies for targeting specific microorganisms. Our aim is to capture the microbes in viable and concentrated form even from less populated samples, with lesser time compared to the presently available methods.

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LW1 145 Using advanced oxidation treatment for biofilm inactivation by varying water vapor content in air plasma* SUGANUMA RYOTA, YASUOKA KOICHI, *Tokyo Tech* Biofilms are caused by environmental degradation in food factories and medical facilities. The inactivation of biofilms involves making them react with chemicals including chlorine, hydrogen peroxide, and ozone, although inactivation using chemicals has a potential problem because of the hazardous properties of the residual substance and hydrogen peroxide, which have slow reaction velocity. We successfully performed an advanced oxidation process (AOP) using air plasma. Hydrogen peroxide and ozone, which were used for the formation of OH radicals in our experiment, were generated by varying the amount of water vapor supplied to the plasma. By varying the content of the water included in the air, the main product was changed from air plasma. When we increased the water content in the air, hydrogen peroxide was produced, while ozone peroxide was produced when we decreased the water content in the air. By varying the amount of water vapor, we realized a 99.9% reduction in the amount of bacteria in the biofilm when we discharged humidified air only.

*This work was supported by JSPS KAKENHI Grant Number 25630104.

LW1 146 Proliferation enhancement of budding yeast and mammalian cells with periodic oxygen radical treatment* YOSUKE MORI, JUN KOBAYASHI, TOMIYASU MURATA, *Meijo University* HIROSHI HAHIZUME, MASARU HORI, *Institute of Innovation for Future Society, Nagoya University* MASAFUMI ITO, *Meijo University* Recently, nonequilibrium atmospheric-pressure plasmas have been intensively studied for biological applications. However, the each effect of species in plasmas to biological tissue has not been clarified yet because various factors exist in the plasmas. Accordingly, we have studied effects of atomic oxygen dose on cell growth such as budding yeast and mouse NIH3T3 fibroblasts of mammalian cells. Both of cells were suspended with PBS, and treated using oxygen radical source. In order to prevent the radicals from reacting with the ambient air, the treatment region was surrounded by a plastic cover and purged with Ar. The proliferative effect of 15% was observed at the $O\left({}^3P_j\right)$ dose of around $1.0 \times 10^{17}\mathrm{cm}^{-3}$ in NIH3T3 cells as well as in yeast cells. Moreover, periodic oxygen treatment enhanced the effect in budding yeast cells. The best interval of periodic oxygen radical treatment was around 2 hours, which is almost the same period as that of their cell cycle. With the optimum interval time, we have investigated the effect of the number of the treatments. As the number of treatments increases, the growth rate of budding yeast cells was gradually enhanced and saturated at thrice treatments.

*This work was partly supported by JSPS KAKENHI Grant Numbers 26286072 and project for promoting Research Center in Meijo University.

LW1 147 Effects of solutions treated with oxygen radicals in neutral pH region on inactivation of microorganism* TSUYOSHI KOBAYASHI, *Meijo University* HIROSHI HASHIZUME, *Nagoya University* TAKAYUKI OHTA, *Meijo University* KENJI ISHIKAWA, MASARU HORI, *Nagoya University* MASAFUMI ITO, *Meijo University* The inactivation of microorganisms using nonequilbrium atmospheric pressure plasmas has been attracted much attention due to the low temperature processing and high speed treatment. In this study, we have inactivated E. coli suspended in solutions with neutral pH using an atmospheric-pressure oxygen radical source which can selectively supply electrically neutral oxygen radicals. E. coli cells were suspended with deionized distilled water (DDW) (pH = 6.8) or phosphate buffered saline (PBS) (pH = 7.4) or Citrate-Na buffer (pH = 6.5). The treated samples were diluted and spread on nutrient agar (Nutrient Broth). They were cultured at 37° C. The inactivation effects of oxygen radicals on those cells in solutions were evaluated by colony-counting method. O2 diluted by Ar gas were employed as a working gas for the radical source. The total gas flow rate and the gas mixture ratio of O2/(Ar+O2) were set at 5 slm and 0.6%, respectively. The distance between the radical exit and the suspension surface were set at 10 mm. As a result, the D values for DDW(pH = 6.8), PBS(pH = 7.4) and Citrate-Na buffer(pH = 6.5) were estimated to be 1.4 min, 0.9 min and 16.8 min respectively. The inactivation rates in DDW, PBS were significantly different from that in Citrate-Na buffer.

*This work was partly supported by JSPS KAKENHI Grant Number 26286072 and project for promoting Research Center in Meijo University.

LW1 148 Effect of medium treated with neutral oxygen radicals on growth of *Saccharomyces cerevisiae** JUN KOBAYASHI, *Meijo University* HIROSHI HASHIZUME, *Nagoya University* TAKAYUKI OHTA, *Meijo University* MASARU HORI, *Nagoya University* MASAFUMI ITO, *Meijo University* Recently, nonequilibrium atmospheric-pressure plasmas are expected to be applied in medical and agricultural fields. We have studied the growth effect of budding yeast cells in phosphate buffered saline (PBS(-)) using an atmospheric-pressure oxygen-radical source. From a practical application perspective, we have investigated the effect of medium treated with oxygen radicals on the growth of budding yeast in the study. The cells were suspended with yeast extract peptone dextrose (YPD) medium or PBS. The suspensions were treated with neutral oxygen radicals. Oxygen radicals were generated at an $O_2/(O_2+Ar)$ gas flow ratio of 0.6%, a total flow rate of 5 slm, and an exposure distance of 10 mm. To estimate the inactivation and the growth of yeast cells, cells were counted with the colony count method using a counting chamber and a microscope. In the case of budding yeast suspended in PBS, the growth changed from promotion to inactivation with increasing the oxygen radical treatment time. But in the case of budding yeast suspended in YPD, it didn't exhibit promotion and inactivation of the growth with oxygen radical treatment. The results indicated that some substances of YPD scavenged the growth effect of oxygen radicals.

*This work was partly supported by JSPS KAKENHI Grant Number 26286072 and project for promoting Research Center in Meijo University.

LW1 149 PLASMA MEDICINE

LW1 150 Verification of antitumor effect in vivo using nanosecond pulsed streamer discharge KENTA YONETAMARI, YUKI SHIRAKAWA, TAKETOSHI AKIYAMA, KAZUE MIZUNO, RYO ONO, *The University of Tokyo* Cancer treatment using plasma has intensively studied these days. In this work, antitumor effect by nanosecond pulsed streamer discharge was investigated. Nanosecond pulsed streamer plasma was used as a plasma source, which can generate stable streamer discharge by using a nanosecond pulsed power supply. The rod electrode of 3 mm diameter is made of copper. Its end is formed into a semispherical shape of 1.5 mm curvature. The electrode is inserted into a quartz tube (inner diameter: 4 mm, thickness: 1 mm) concentrically, so any gas can be introduced. B16F10 cells were selected to perform in vivo antitumor study. These cells were injected under the skin of leg of mice to make cancer tumor. One week later from injections, plasma was applied to the cancer tumor. Mice were randomly assigned into three groups which were one control group and two plasma treatment groups. In the control group, mice were not treated. In the plasma treatment groups, plasma with dry N_2 and wet O_2 as a working gas were irradiated for 5 consecutive days. Processing time was 10 min and the gap distance between the electrode and tumor was 4 mm. After 5 days plasma treatment, antitumor effect was observed. The result indicates that the streamer discharge has a potential for cancer treatment.

LW1 151 Sterilization of *Bacillus atrophaeus* using OH radicals supplied by vacuum ultraviolet method KENTA YONETAMARI, YUSUKE TOKUMITSU, SEIYA YONEMORI, RYO ONO, *The University of Tokyo* HACHIRO YASUDA, AKIRA MIZUNO, *Toyohashi University of Technology* Sterilization by cold plasma has widely been performed. It is well known that reactive oxygen species (ROS) has a potential of sterilization. However, it is not clear which ROS is effective on sterilization because a lot of types of ROS are produced in plasma. In this study, sterilization effect of OH radicals by vacuum ultraviolet (VUV) method was investigated. This method utilizes photodissociation reaction to produce ROS so it can produce ROS selectively. Wet and dry helium with and without 1% O2 gas was used to demonstrate sterilization effect of OH radicals. Gases were flowed in a quartz tube (inner diameter 2 mm, outer diameter 4 mm) at a flow rate of 1.5 L/min. The produced ROS flowed out of the quartz tube nozzle. A Xe2 excimer lamp emitting 172 ± 7 nm VUV light was placed parallel to the quartz tube with a distance of 8 mm. The distance between the lower end of the lamp and the nozzle of quartz tube was changed from 3 to 15 cm. As a target of sterilization, *Bacillus atrophaeus* (ATCC 9372) was used. The density of OH radicals was measured using laser-induced fluorescence (LIF). As a result, sterilization using VUV method was verified. This result showed that OH radicals sterilized the bacteria.

LW1 152 The comparison of DNA damage induced by micro DBD plasma and low energy electron for curing human diseases YEUNSOO PARK, *National Fusion Research Insititute* It is well known that low energy electrons (LEE, especially below 10 eV) can generate DNA damage via indirect action named dissociative electron attachment (DEA). We can now explain some parts of the exact mechanism on DNA damage by LEE collision with direct ionization effect when cancer patients get the radiotherapy. It is kind of remarkable information in the field of radiation therapy. However, it is practically very difficult to directly apply this finding to human disease cure due to difficulty of LEE therapy actualization and request of further clinical studies. Recently, there is a novel challenge in plasma application, that is, how we can apply plasma technology to diagnosis and treatment of many serious diseases like cancer. Cold atmospheric pressure plasma (CAPP) is a very good source to apply to plasma medicine and bio-applications because of low temperature, low cost, and easy handling. Some scientists have already reported good results related to clinical plasma application. The purposes of this study are to further find out exact mechanisms of DNA damage by LEE at the molecular level, to verify new DNA damage like structural alteration on DNA subunits and to compare DNA damage by LEE and plasma source. We will keep expanding our study to DNA damage by plasma source to develop plasma-based new medical and biological applications. We will show some recent results, DNA damage by LEE and non-thermal plasma.

LW1 153 Investigation of Sterilization Mechanism for *Geobacillus stearothermophilus* Spores with Plasma-Excited Neutral Gas KEI MATSUI, NORIAKI IKENAGA, NORIYUKI SAKUDO, *Kanazawa Institute of Technology* We investigate the mechanism of the sterilization with plasma-excited neutral gas that uniformly sterilizes both the space and inner wall of the reactor chamber at atmospheric pressure. Only reactive neutral species such as plasma-excited gas molecules and radicals are separated from the plasma and sent to the reactor chamber for chemical sterilization. The plasma source gas uses humidified mixture of nitrogen and oxygen. *Geobacillus stearothermophilus* spores and tyrosine which is amino acid are treated by the plasma-excited neutral gas. Shape change of the treated spore is observed by SEM, and chemical modification of the treated tyrosine is analyzed by HPLC. As a result, the surface of the treated spore shows depression. Hydroxylation and nitration of tyrosine are shown after the treatment. For these reasons, we believe that the sterilization with plasma-excited neutral gas results from the deformation of spore structure due to the chemical modification of amino acid.

LW1 154 Material Compatibility of Medical Sterilizer Using Oxygen Plasma HIROSHI TANAKA, REOTO ONO, NOBUYA HAYASHI, *Kyushu University* YASUSHI HANADA, *Elquest Co. Ltd.* MINORU NODA, MASAAKI GOTO, *Saga University* Material compatibility of oxygen plasma sterilizer is investigated comparing with hydrogen peroxide (H_2O_2) sterilizers and a gaseous H_2O_2 sterilizer. Organic materials such as ABS, PE, PP, and PET are used as sample materials, and are irradiated by active oxygen species produced in oxygen plasma. After plasma irradiation, surface of the sample materials is observed using a scanning electron microscope and FTIR spectroscopy. Strengths of the organic materials are evaluated by the tension test. Also, H_2O_2 plasma sterilizer and a gaseous H_2O_2 sterilizer those are commercially available are utilized to compare the material compatibility, especially organic compounds. The ABS resin becomes slightly soft after irradiation by both plasmas and gaseous H_2O_2. Also, PET material becomes soften by each sterilization treatment. Decrease of peak heights of CH around 1200 and 1730 cm^{-1} and increase of that of OH at 3300 cm^{-1} in FTIR spectra indicates the oxidation of ABS resin by both plasma and gaseous H_2O_2. In the case of PET material, treatment by the plasma has not modified chemical composition but changed the crystal structure. The gaseous H_2O_2 is completely friendly for the PET material.

LW1 155 Spatially-Selective Membrane Permeabilization Induced by Cell-Solution Electrode Atmospheric Pressure Plasma Irradiation SHOTA SASAKI, YUTARO HOKARI, *Department of Electronic Engineering, Tohoku University* MAKOTO KANZAKI, *Department of Biomedical Engineering, Tohoku University* TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University* Gene transfection, which is the process of deliberately introducing nucleic acids into cells, is expected to play an important role in medical treatment because the process is necessary for gene therapy and creation of induced pluripotent stem (iPS) cells. However, the conventional transfection methods have some problems, so we focus attention on promising transfection methods by atmospheric pressure plasma (APP). We have previously reported that the cell membrane permeability, which is closely related with gene transfection, is improved using a cell-solution electrode for generating He-APP [1, 2]. He-APP is irradiated to the solution containing the adherent cells and delivery materials such as fluorescent dyes (YOYO-1) and plasmid DNA (GFP). In case of YOYO-1 delivery, more than 80% of cells can be transferred only in the plasma-irradiated area and the spatially-selective membrane permeabilization is realized by the plasma irradiation. In addition, it is confirmed that plasmid DNA is transfected and the GFP genes are expressed using same APP irradiation system with no obvious cellular damage.

[1]S. Sasaki, M. Kanzaki, and T. Kaneko, Appl. Phys. Express **7**, 026202 (2014).

[2]T. Kaneko, S. Sasaki, Y. Hokari, S. Horiuchi, R. Honda, and M. Kanzaki, Biointerphases **10**, 029251 (2015).

LW1 156 Measurement of plasma-generated RONS in the cancer cells exposed by atmospheric pressure helium plasma jet HEA MIN JOH, EUN JEONG BAEK, SUN JA KIM, TAE HUN CHUNG, *Dong-A University* The plasma-induced reactive oxygen and nitrogen species (RONS) could result in cellular responses including DNA damages and apoptotic cell death. These chemical species, O, O_2^-, OH, NO, and NO_2^-, exhibit strong oxidative stress and/or trigger signaling pathways in biological cells. Each plasma-generated chemical species having biological implication should be identified and quantitatively measured. For quantitative measurement of RONS, this study is divided into three stages; plasma diagnostics, plasma-liquid interactions, plasma-liquid-cell interactions. First, the optical characteristics of the discharges were obtained by optical emission spectroscopy to identify various excited plasma species. And the characteristics of voltage-current waveforms, gas temperature, and plume length with varying control parameters were measured. Next, atmospheric pressure plasma jet was applied on the liquid. The estimated OH radical densities were obtained by ultraviolet absorption spectroscopy at the liquid surface. And NO_2^- is detected by Griess test and compared between the pure liquid and the cell-containing liquid. Finally, bio-assays were performed on plasma treated human lung cancer cells (A549). Intracellular ROS production was measured using DCF-DA. Among these RONS, productions of NO and OH within cells were measured by DAF-2DA and APF, respectively. The data are very suggestive that there is a strong correlation among the production of RONS in the plasmas, liquids, and cells.

LW1 157 Sterilization Performance and Material Compatibility of Sterilizer for Dental Instruments using RF Oxygen Plasma YASUHIRO SAKAI, ZHEN LIU, NOBUYA HAYASHI, *Kyushu University* MASAAKI GOTO, *Saga University* The sterilization performance and material compatibility of low-pressure RF plasma sterilization method for dental instruments were investigated. RF electrode used in this experiment has been optimized for sterilization of dental instruments. The vial-type biological indicator (BI) simulating tiny space of dental instrument was used for evaluation of the sterilization performance. The pressure in the stainless chamber was fixed at 60 Pa. Sterilization of BI was achieved in shortest time 40 min at 80 W, and the sterilization effect was confirmed using three BIs. Light emission spectra of oxygen plasma indicated that production of atomic oxygen and excited oxygen molecule are maximum at pressure of 20 Pa and 200 Pa, respectively. Sterilization results of BIs indicated that successful rate increases with the oxygen pressure towards 200 Pa. Therefore, the excited oxygen molecule is deduced to be a major factor of the sterilization of BI. Surface morphology of dental instruments such as diamond bar was evaluated using scanning electron microscope (SEM). The deterioration of fine crystals of diamond bar has not observed after the plasma irradiation for 120 min with RF input power was 60W and pressure was 200 Pa.

LW1 158 Synthesis of indium-containing nanoparticles using plasmas in water to study their effects on living body TAKAAKI AMANO, KAZUNORI KOGA, THAPANUT SARINONT, HYUNWOONG SEO, NAHO ITAGAKI, MASAHARU SHIRATANI, *Graduate School of Information Science and Electrical Engineering, Kyushu University* SATOSHI KITAZAKI, *Graduate School of Electrical Engineering, Fukuoka Institute of Technology* MIYUKI HIRATA, YOSHIMICHI NAKATSU, AKIYO TANAKA, *Faculty of Medical Sciences, Kyushu University* Nanoparticles can be employed for biomedical applications such as biomarkers, drug delivery systems, and cancer therapies. They are, however, pointed out their adverse effects on human body. Here, we synthesed indium-containing nanoparticles using discharge plasmas with indium electrodes immersed in DI water and administrated nanoparticles to rats to analyze their kinetics in living body. The discharge power was 5.1 W. The electron density is $5x10^{17}/cm^3$ deduced from Stark broadening of hydrogen lines. TEM observation shows the mean size of primary nanoparticles is 7 nm. The nanoparticles are indium crystalline and indium hydroxide crystalline. The synthesized nanoparticles and purchased nanoparticles (In_2O_3, <100nm) were administrated to rats using subcutaneous injection. Indium of 166.7 g/day (synthesized) and of 27.8 g/day (purchased) are detected from the urine at 12 weeks after the administration. Synthesized nanoparticles dispersed in water are useful for analyzing kinetics of nanoparticles in living body. Work partly supported by KAKENHI.

LW1 159 Analysis of non-thermal plasma-induced cell injury in human lung cancer cell lines* HIROFUMI KURITA, KAORI SANO, MOTOI WADA, *Toyohashi University of Technology* KAZUE MIZUNO, RYO ONO, *The University of Tokyo* HACHIRO YASUDA, KAZUNORI TAKASHIMA, AKIRA MIZUNO, *Toyohashi University of Technology* Recent progress of biomedical application of atmospheric pressure plasma shows that the biological effects are mainly due to reactive oxygen and nitrogen species (RONS) in liquid produced by the plasma exposure. To elucidate the cellular responses induced by exposure to the plasma, we focused on identification and quantification of reactive chemical species in plasma-exposed cell culture medium, and cell injury in mammalian cells after treatment of the plasma-exposed medium. In this study, we examined human lung cancer cell lines. The contribution of H_2O_2 to the cellular responses was considered. Here, an atmospheric pressure plasma jet (APPJ) sustained by a pulsed power supply in argon was used. After APPJ exposure to cell culture medium, RONS detection in liquid was conducted. It showed that OH radical, $ONOO^-$, NO_2^-, NO_3^-, and H_2O_2 were produced in the plasma-exposed medium. Cellular responses of human lung cancer cell lines to the plasma-exposed medium in a concentration-dependence manner were also studied. It showed that the plasma-exposed medium and the H_2O_2 treatment gave similar reduction in viability and induction of apoptosis.

*This work was partly supported by MEXT KAKENHI Grant Number 24108005 and JSPS KAKENHI Grant Number 26390096.

LW1 160 The effect of the suspension cells in plasma gene transfection method* YUKI ISOZAKI, KOKI NAKANO, YOSHIHISA IKEDA, HIDEKI MOTOMURA, *Department of Electrical and Electronic Engineering, Ehime Univ* YUGO KIDO, *Pearl Kogyo Co.Ltd* SUSUMU SATOH, *Y's Corporation* KUNIHIDE TACHIBANA, *Department of Electrical and Electronic Engineering, Osaka Electro-Communication Univ* MASAFUMI JINNO, *Department of Electrical and Electronic Engineering, Ehime Univ* Plasma gene transfection method is a unique technique for introducing nucleic acids into cells by using plasma irradiation. In our previous works, plasma gene transfection method was performed for the adherent cells, e.g. COS-7 cells, and the influence of plasma on gene transfection has been investigated. As a next step for plasma medicine, transfection to much more various kinds of target cells is required. In this study, the authors attempted gene transfection to two kinds of suspension and four kinds of adherent cells. Although the transfection ratios to the suspension cells were low, transfection to all the kinds of cells were validated. To upregulate the transfection ratio for suspension cells, the authors are validating related factors by plasma irradiation.

*This work was partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas (Number 25108509, 15H00896) and a grant from Ehime University.

LW1 161 Investigation on Large Molecule Permeation through Liposome Lipid Bilayer Induced by Microplasma Irradiation* HIDENORI NAGAIWA, DAIJIRO AIBARA, YOSHIHISA IKEDA, HIDEKI MOTOMURA, *Department of Electrical and Electronic Engineering,Ehime University* YUGO KIDO, *Pearl Kogyo Co.Ltd* SUSUMU SATOH, *Y's Corporation* KUNIHIDE TACHIBANA, *Department of Electrical and Electronic Engineering,Osaka Electro-Communication University* MASAHUMI JINNO, *Department of Electrical and Electronic Engineering,Ehime University* The authors have been developing a novel gene transfection method using microplasma irradiation. In order to clarify the mechanism of large molecule permeation process through the lipid bilayer, plasma induced outflow of hydrophilic fluorescent dye molecules, which were encapsulated in the liposome, was observed. By microplasma irradiation on the liposome suspension, the dyes flowed out from the inside of the liposomes. The outflow of the dyes was enhanced by longer plasma irradiation time. Investigation of the outflow mechanism, i.e. permeation enhancement of the lipid bilayer or burst of the liposome, is under progress.

*This work was partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas (Number 25108509,15H00896) and a grant from Ehime University.

LW1 162 Influence of the H_2O_2 in the plasma gene transfection method* MASANORI KIMURA, HIROKI TACHIBANA, YUKI OHNO, YOSHIHISA IKEDA, HIDEKI MOTOMURA, *Depertment of Electrical and Electronic Engineering, Ehime Univ* YUGO KIDO, *Pearl Kogyo Co.Ltd* SUSUMU SATOH, *Y's Corporation* KUNIHIDE TACHIBANA, *Depertment of Electrical and Electronic Engineering, Osaka Electro-Communication Univ* MASAFUMI JINNO, *Depertment of Electrical and Electronic Engineering, Ehime Univ* Gene transfection is the process of deliberately introducing nucleic acids into cells. The authors have been developing a novel gene transfection method using microplasma irradiation (plasma gene transfection method). Our previous study shows that long life chemically reactive species contribute to gene transfection, which induce the transfection at least 60 s after plasma irradiation (after effect). In order to clarify the key reactive species which is effective on the after effect, the effect of H_2O_2 addition after plasma irradiation was investigated. Addition of H_2O_2 at 1/1000−1 ppm after plasma irradiation did not largely affect or slightly decease the transfection ratio, whereas the H_2O_2 concentration induced by plasma irradiation is estimated as 2.7 ppb after dilution by the medium. It is found that the H_2O_2 is not main species for the after effect.

*This work was partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas (Number 25108509, 15H00896) and a grant from Ehime University.

LW1 163 Effect of the cell temperature in the plasma gene transfection* YOSHIHISA IKEDA, KUNIMORI MANABE, YUKI ISOZAKI, HIDEKI MOTOMURA, *Ehime University* YUGO KIDO, *Pearl Kogyo Co. Ltd.* SUSUMU SATOH, *Y's Corporation* KUNIHIDE TACHIBANA, *Osaka Electro-Communication University* MASAFUMI JINNO, *Ehime University* The authors study effect of the cells temperature in the plasma gene transfection by changing temperature of the GND electrode from 5 °C and to 55 °C to identify the mechanism of transfection by plasma. By increasing the GND electrode temperature, the transfection ratio increased up to 45 °C and then decreased at higher temperature. The best fitting curve indicates that the optimum temperature for the maximum transfection ratio, which is 1.25 times higher than that at room temperature, is approximately 40 °C. In general, activation of cells will be also maximum around this temperature. Therefore, it is suggested that the cell activation enhances the gene transfection ratio under plasma irradiation.

*This work was partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas (Number 25108509, 15H00896) and a grant from Ehime University.

LW1 164 Characteristics of Surface Sterilization using ECR Plasma AKIRA YONESU, KAZUFUMI HARA, TATSUYA NISHIKAWA, *University of the Ryukyus* NOBUYA HAYASHI, *Kyushu University* Plasma sterilization techniques have superior characteristics such as a short treatment times, non-toxicity and low thermal damages on the sterilized materials. In plasma sterilization, microorganisms can be sterilized by active radicals, energetic charged particles, and vacuum UV radiation. The influence of each factor depends on the plasma operating parameters. Microwave discharges under the electron cyclotron resonance (ECR) condition produce higher electron temperature and density plasma as compared with other plasma generation techniques. In the present study, characteristics of surface sterilization using ECR plasma have been investigated.The experiment was performed in the vacuum chamber which contains a magnet holder. A pair of rectangular Sm-Co permanent magnets is aligned parallel to each other within the magnet holder. The region of the magnetic field for ECR exists near the magnet holder surface. When the microwave is introduced into the vacuum chamber, a ECR plasma is produced around surface of the magnet holder. High energy electrons and oxygen radicals were observed at ECR zone by electric probe method and optical spectroscopic method. Biological indicators (B.I.) having spore of 10^6 was sterilized in 2min for oxygen discharge. The temperature of the B.I. installation position was about 55°. The sterilization was achieved by the effect of oxygen radicals and high energy electrons.

LW1 165 PLASMAS FOR NANOTECHNOLGIES, FLEXIBLE ELECTRONICS AND OTHER EMERGING APPLICATIONS

LW1 166 Domain control of ZnO nanoparticles in a coaxial gas-flow pulse Ar/O_2 plasma SATORU IIZUKA, HIROKI SHIRAHATA, *Graduate School of Engineering, Tohoku University* A limited area, to which ZnO nanoparticles are selectively adhered, is called a domain. Formation of the domain was controlled by using a coaxial gas-flow pulse Ar/O_2 plasma. It was found that the mechanism of domain formation was closely related to the initial surface condition of Si substrate. Especially, the cleaning process was crucial. Here, we employed a patterning of the domain by using a fine mesh as a template. The formation processes were estimated by SEM and EDX. The technique developed here will be applied to a selective nanoparticle patterning.

LW1 167 Characterization of self-assembled silver pattern forming in argon and ammonia mixed atmospheric pressure plasma NAOYA KIHARA, ELLA BLANQUET, *Kyoto University, The University of Shiga Prefecture* YU HIRAOKA, *Kyoto University* OSAMU SAKAI, *Kyoto University, The University of Shiga Prefecture* Self-assembly fractal-like silver pattern was observed when the silver nitrate solution was dried with the gas flow of argon and ammonia mixed atmospheric plasma. This process can generate hydrazine, which is a powerful reductive agent, and silver particles are deposited from silver nitrate self-assembly [1] and form fractal-like pattern in sub-μm order. This pattern shows abnormal optical response, so our self-assembly plasma process will be likely to bring a good method to make optical metamaterials because of its simplicity. In addition, we proposed that this process is applicable for widely sensitive metamaterials process, since we made sub-μm and several ten micrometers mingled microstructure through the plasma process with the use of micro particles. We diagnosed the characteristics of this typical pattern by Fourier transform infrared spectroscopy and numerical simulation, and confirmed that the pattern was widely sensitive from mid-infrared to far-infrared region. We aim at controlling the typical response phenomena and making widely sensitive optical metamaterials with changing deposition condition.

[1]K. Urabe, Y. Hiraoka, and O. Sakai, Plasma Sources Sci. Technol. **22**, 032003 (2013).

LW1 168 Effects of Flux and Energy of Neutral Beam on Hydrogenation of Graphene TAKERU OKADA, *Institute of Fluid Science, Tohoku University* SEIJI SAMUKAWA, *WPI-AIMR, Tohoku University* Hydrogen modification, hydrogenation, of graphene, has attracted due to the possibility of hydrogen storage. Chemisorbed hydrogen has strong interaction with graphene surface and sp3 bond forms. Surprisingly, ideal structure of graphene shows reversible absorption of hydrogen and it leads to effective designing of hydrogen storage material. In this paper, we have demonstrated neutral beam (NB) technique for hydrogenation of graphene instead of conventional plasma method. NB system consists of a plasma generation chamber and a process chamber, which are separated by a carbon plate with many apertures. The charged particles can be effectively neutralized by collision with the sidewall of the apertures when passing through them to the process chamber. Development of the D-band and blue shift of G-band were observed after hydrogen NB irradiation by Raman spectroscopy. FTIR analysis reveals CH bending mode was appeared and it depends on beam energy, thus CH formation has reaction threshold and potential to control it. In addition, it is shown that beam flux affects hydrogenation and additional effect is also included in reaction process. We believe our investigation will provide development of hydrogenated graphene applications.

LW1 169 Oxygen sensitivity of zinc oxide nanoparticles produced via laser-ablated plasma in pressurized liquid TAKU GOTO, *Osaka University* YOSHIKI SHIMIZU, *National Institute of Advanced Industrial Science and Technology* TSUYOHITO ITO, *Osaka University* While traditional semiconductor oxygen sensor operate only with elevated temperature (*badhbox* 700 K), the room-temperature operation of the ZnO oxygen sensors have been demonstrated with the help of UV light irradiation. Especially, ZnO nanotubes and nanoparticles have attracted much attentions as highly sensitive oxygen sensors and photodetectors. To the best of our knowledge, the reported works of gas sensors with ZnO nanostructures have been mostly intended for revealing effects of the morphology/shape and the size of the nanostructures. For further improvements of the ZnO-based gas sensors, it is probably required to understand effects of microscopic structures, such as densities of various defects. In this study, we synthesized the ZnO nanoparticles with various defects by means of laser-ablated plasma in pressurized water-ethanol mixture. The results indicate that the defects in ZnO affect oxygen sensitivity, and especially VO+ defects seem to be mostly responsible for the resistance change of ZnO nanoparticles. We demonstrate that partial oxygen pressure can be measured with high sensitivity.

LW1 170 Plasma-induced processing in microdroplets for nanoparticles synthesis MASANAO TSUMAKI, *Osaka University* YOSHIKI SHIMIZU, *National Institute of Advanced Industrial Science and Technology* TSUYOHITO ITO, *Osaka University* Plasma processing in microdroplets is studied, as the solute of organic compounds in the microdroplets is a raw material for nanoparticles synthesis. Synthesis of ZnO nanoparticles with wurtzite structure and control of their size distribution with regulating the zinc acetate ($Zn(Ac)_2$) solution concentration are achieved. The plasma is generated by means of dielectric barrier discharges in He gas flow, and the generated particles are analyzed by photoluminescence spectroscopy, scanning electron microscopy, and transmission electron microscopy. The size distribution shifted with the increase of $Zn(Ac)_2$ concentration, and the average sizes are expected by assuming one ZnO nanoparticle is formed from one microdroplet with known $Zn(Ac)_2$ density. The properties of nanoparticles are independent of the solution concentration within the tested range (0.5-2 mM), except of their sizes. The results strongly suggest that one microdroplet is a closed reaction area, thus providing certain controllability of the generated nanoparticles.

LW1 171 Plasma requirements for vertically aligned carbon nanowalls synthesis LUCIA BONOVA, JANA BOHOVICOVA, JURAJ HALANDA, MARTIN MUSKA, MARCEL MESKO, *Slovak University of Technology* PLASMA TECHNOLOGIES AND PLASMA SURFACE INTERACTIONS TEAM Graphene related nanostructures have large potential in energy storage applications because of their unique physical and chemical properties. Carbon nanowalls (CNWs) are practical realization of graphene containing nanostructures. CNWs are two-dimensional carbon structures that consist of stacked graphene sheets standing vertically on substrates. Vertically aligned carbon nanowalls were synthetized by atmospheric direct current plasma enhanced chemical vapor deposition. The CNWs nucleation and aligned mechanism on catalytically active surfaces were revealed. Importance of plasma conditions for vertically aligned CNWs synthesis is evidenced by analyzing both outside and inside growth area.

LW1 172 Plasma Properties of Superimposed Dual Frequency Inductively Coupled Plasma Source TAE HYUNG KIM, SEUNG MIN LEE, CHUL HEE LEE, JEONG OUN BAE, KYONG NAM KIM, GEUN YOUNG YEOM,* *Sungkyunkwan University* Plasma characteristics of internal linear inductively coupled plasma sources using dual frequency composed 2 and 13.56 MHz were investigated. Improved plasma characteristics such as higher plasma density, lower electron temperature, and plasma non-uniformity were observed with the dual frequency. Therefore, by using the dual frequency to the U-shaped ICP source, not only the plasma density but also plasma uniformity could be improved in addition to the decrease of possible damage to the substrate.

*corresponding author

LW1 173 The characteristics of the thin wall carbon nanotube after treatment with capacitively coupled plasma and inductively coupled plasma HUNSU LEE, WOOYOUNG KIM, YONG CHAE JUNG, *KIST* The treatment of the carbon nanotubes with plasma is being reported as an effective method to enhance the dispersion properties and functionalization. The characteristics of carbon nanotube such as the degree of defect of atomic composition differs according to the plasma source used for the treatment and the difference affect the electrical or mechanical properties of the composite materials using the nanotube as filler. In this poster, the effect of plasma treatment with capacitively coupled plasma and inductively coupled plasma on the characteristics and the measured plasma parameters is discussed. The ion bombardment energy on the surface of the nanotube, electron temperature and electron density affected the characteristics of the carbon nanotube and the control of the carbon nanotube composite is thought to be enabled with proper selection of the plasma source for the treatment.

LW1 174 Plasma – enhanced dispersion of metal and ceramic nanoparticles in polymer nanocomposite films* PAUL MAGUIRE, *University of Ulster* YAZI LIU, *Nanjing University, China* SADEGH ASKARI, JENISH PATEL, MANUEL MACIA-MONTERO, SOMAK MITRA, *University of Ulster* RICHAO ZHANG, *Nanjing University Jinling College, China* DAN SUN, *Queen's University Belfast* DAVIDE MARIOTTI, *University of Ulster* In this work we demonstrate a facile method to synthesize a nanoparticle/PEDOT:PSS hybrid nanocomposite material in aqueous solution through atmospheric pressure direct current (DC) plasma processing at room temperature. Both metal (Au) and ceramic (TiO_2) nanoparticle composite films have been fabricated. Nanoparticle dispersion is enhanced considerable and remains stable. TiO_2/polymer hybrid nanoparticles with a distinct core shell structure have been obtained. Increased nanoparticle/PEDOT:PSS nanocomposite electrical conductivity has been observed. The improvement in nanocomposite properties is due to the enhanced dispersion and stability in liquid polymer of microplasma processed Au or TiO_2 nanoparticles. Both plasma induced surface charge and nanoparticle surface termination with specific plasma chemical species are thought to provide an enhanced barrier to nanoparticle agglomeration and promote nanoparticle-polymer bonding. This is expected to have a significant benefit in materials processing with inorganic nanoparticles for applications in energy storage, photocatalysis and biomedical sensors.

*Engineering and Physical Sciences Research Council (EPSRC: EP/K006088/1, EP/K006142, Nos. EP/K022237/1).

LW1 175 Characterization of a K-Band Plasma Controlled Photonic Crystal* DAVID BIGGS, MARK CAPPELLI, *Stanford University* The effect of a low-pressure plasma column on a resonant cavity in a miniature photonic crystal is studied experimentally and computationally. The photonic crystal is created using a square array of alumina rods with the center rod removed to create the resonant cavity. Out of plane radiative losses are minimized by a copper waveguide on either side of the photonic crystal. The plasma column is formed by a kHz discharge in argon gas at <1 Torr. The bandgap and defect state properties of the photonic crystal with and without a plasma column are measured using a vector network analyzer. The time resolved history of the plasma discharge is measured with a crystal detector. The experiments are compared with simulations using a finite difference time domain electromagnetic solver and a simple Drude model of the plasma column.

*Sponsored by the AFOSR MURI.

LW1 176 Releasing of Sputtered Au Film by Dissolving Sacrificial Layer and Its Self-Standing on Perforated Substrate* YU MIYAMOTO, YUMA FUJII, MASAFUMI YAMANO, TORU HARIGAI, YOSHIYUKI SUDA, HIROFUMI TAKIKAWA, *Department of Electrical & Electronic Information Engineering, Toyohashi University of Technology* MAMIKO NISHIUCHI, HIRONAO SAKAKI, KIMINORI KONDO, *Japan Atomic Energy Agency* Free-standing thin films such as diamond-like carbon (DLC) and gold (Au) have been attracted increasing interests as film targets used in the laser-driven ion acceleration experiment [1]. One of the methods to make the free-standing thin film is to use a soluble sacrifice layer [2]. In this study, the fabrication technique of self-standing Au thin film is presented. Gelatin, oblate, silk fibroin, and NaCl were examined as a. Au thin films were deposited by DC plasma sputtering on sacrifice layers. The gelatin and oblate were used as the sacrificial layer and the supporting substrate. Silk fibroin was coated on glass substrates by a spin coater. The NaCl sacrificial layers were deposited on flat Si substrates by the vacuum vapor deposition system. Sputtered Au thin films were released by immersing the substrates in purified water. Self-standing Au thin films were fabricated by scooping up the released Au thin film on a perforated substrate. The highest quality of the self-standing Au thin film was achieved by using NaCl sacrificial layer.

*This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research and Toukai Foundation for Technology.

[1]M. Nishiuchi, J. Plasma Fusion Res. **88**, 5 (2012).
[2]F. Gao *et al.*, Nucl. Instr. Meth. A **577**, 397 (2007).

LW1 177 A study of a split ring resonator response to free-space Ku band excitation in the presence of a gap plasma discharge* JACK GOODWIN, ROBERTO COLON QUINONES, FABIO RIGHETTI, BEN WANG, MARK CAPPELLI, *Stanford University* Split-ring resonators are commonly used elements in metamaterials. Their L-C resonance drives a permeability that can take on negative values affording novel interactions with free space radiation. The capacitance is partially dictated by the split ring gap. In this study, we examine both theoretically and experimentally, the electromagnetic response of a split ring resonator, and arrays of resonators, to incident Ku band radiation under conditions in which a gas discharge or laser-produced plasma is generated in proximity of the gap. The resonance is found to shift towards higher frequencies, consistent with what is expected from simple theoretical modeling.

*This research is supported by the Air Force Office of Scientific Research through a Multi-University Research Initiative.

LW1 178 Atmospheric Pressure Micro-Thermal-Plasma-Jet Crystallization of Amorphous Silicon Strips for High-Performance Thin Film Transistor Fabrication* SEIJI

MORISAKI, TAICHI NAKATANI, RYOTA SHIN, SEIICHIRO HIGASHI, *Graduate School of Advanced Sciences of Matter, Hiroshima University* Zone melting recrystallization (ZMR) of amorphous silicon (a-Si) strips by micro-thermal-plasma-jet (u-TPJ) irradiation is quite effective to suppress grain boundaries (GBs) except sigma 3 coincidence site lattice (CSL). Intra-grain defects in 1 μm wide strips were significantly reduced by suppressing the agglomeration of molten Si with low temperature condition around melting point of crystalline Si. Thin film transistors (TFTs), using optimized ZMR condition by scanning speed of 1500 mm/s demonstrated extremely high performance with field effect mobility (u_{FE}) of 443 cm^2/Vs and swing factor (S) of 210 mV/dec.

*Part of this work was supported by the Research Institute for Nanodevice and Bio Systems (RNBS), Hiroshima University.

SESSION MW1: ATOMIC AND MOLECULAR SCATTERING DATA FOR PLASMA AND RELATED APPLICATIONS WORKSHOP II

Wednesday Evening, 14 October 2015; Room: 301 B at 20:00; Tom Kirchner, York University, presiding

Invited Papers

20:00

MW1 1 Atomic Data Quality and Needs for Collisional-Radiative Modeling*

YURI RALCHENKO, *National Institute of Standards and Technology*

Reliable calculation of plasma kinetic characteristics and emission and/or absorption spectra necessarily involves large sets of atomic data such as state energies, radiative and autoionization transition probabilities and collisional cross sections or rate coefficients. The quality and extension requirements for such data often depend on a particular problem as various plasmas may exhibit non-Maxwellian distributions, anisotropy effects, or be under strong fields that may modify atomic structure. We will present an overview of the recent efforts on analysis of data quality requirements and data needs for collisional-radiative modeling of diverse plasmas, from magnetic fusion to astrophysics to dense laser-produced plasmas.

*Supported in part by DOE and NASA.

20:30

MW1 2 Charge exchange spectroscopy of multiply charged ions for the development of the EUV light source for the next generation photo lithography

HAJIME TANUMA, *Department of Physics, Tokyo Metropolitan University*

As a candidate of an extreme ultra-violet (EUV) light source for a next generation lithography, laser produced plasmas (LPP) of Xe and Sn have been investigated intensively in this decade because these plasmas have a strong emission around 13.5 nm which had been determined as the wavelength for the EUV lithography. This emission was considered to be due to multiply charged Xe and Sn ions in hot plasmas. However, the detail atomic spectroscopic data of these multiply charged heavy ions had not been reported yet. To provide atomic data for the understanding and development of the LPP as the EUV light source, we have observed the EUV emission spectra from individual charge states of Xe and Sn ions by means of a charge exchange spectroscopy method. Multiply charged Xe^{q+} (q = 7-23) and Sn^{q+} (q = 5-21) ions were produced with a 14.25 GHz electron cyclotron resonance ion source, and a charge-selected ion beam was directed into a collision chamber, where the ion interact with a target gas of He and Xe. EUV emissions from the collision center were observed with a compact flat-field grazing-incident spectrometer equipped with a liquid nitrogen cooled CCD camera. In experiments using Xe ions, we have found only Xe XI has a strong UTA (unresolved transition array) around 13.5 nm. On the other hand, various charge states of Sn from VIII to XIV contribute to the 13.5 nm emission. Identification of the transition lines was carried out by calculations using the Hebrew university Livermore laboratory atomic physics code and the Cowan code. Most of the emissions in the EUV region are attributed to the 4p-4d and 4d-$n\ell$ ($n\ell$ = 4f, 5p, and 5f) transitions. However, the 4d-4f transitions have approximately constant differences of about 0.5 nm between the experimental and theoretical results. This can be explained by considering the strong configuration interactions in the n=4 subshells. Using the experimental transition wavelengths of multiply charged Sn ions, theoretical modeling of radiative properties of Sn plasmas and radiation hydrodynamics simulations had been performed for the optimization of the LPP EUV light source.

21:00

MW1 3 Interactions of Deuterium Plasma with Lithiated and Boronized Surfaces in NSTX-U*

PREDRAG KRSTIC, *State University of New York - Stony Brook*

The main research goal of the presented research has been to understand the changes in surface composition and chemistry at the nanoscopic temporal and spatial scales for long pulse Plasma Facing Components (PFCs) and link these to the overall machine performance of the National Spherical Torus Experiment Upgrade (NSTX-U). A study is presented of the lithium surface science, with atomic spatial and temporal resolutions. The dynamic surface responds and evolves in a mixed material environments (D, Li, C, B, O, Mo, W) with impingement of plasma particles in the energy range below 100 eV. The results, obtained by quantum-classical molecular dynamics, include microstructure changes, erosion, surface chemistry, deuterium implantation and permeation. Main objectives of the research are i) a comparison of Li and B deposition on carbon, ii) the role of oxygen and other impurities e.g. boron, carbon in the lithium performance, and iii) how this performance will change when lithium is applied to a high-Z refractory metal substrate (Mo, W). In addition to predicting and understanding the phenomenology of the processes, we will show plasma induced erosion of PFCs, including chemical and physical sputtering yields at various temperatures (300-700 K) as well as deuterium uptake/recycling.

*This work is supported by the U.S. Department of Energy Office of Science, Office of Fusion Energy Science, Award Number DE-SC0013752.

SESSION NR1: PLASMA SOURCES FOR BIOMEDICAL APPLICATIONS I

Thursday Morning, 15 October 2015; Room: 301 B at 8:00; Alexander Fridman, Drexel University, presiding

Invited Papers

8:00

NR1 1 Design and characterization of an RF excited micro atmospheric pressure plasma jet for reference in plasma medicine*

VOLKER SCHULZ-VON DER GATHEN, *Ruhr-Universität Bochum, Research Department Plasma, 44801 Bochum*

Over the last decade a huge variety of atmospheric pressure plasma jets has been developed and applied for plasma medicine. The efficiency of these non-equilibrium plasmas for biological application is based on the generated amounts of reactive species and radiation. The gas temperatures stay within a range tolerable for temperature-sensitive tissues. The variety of different discharge geometries complicates a direct comparison. In addition, in plasma-medicine the combination of plasma with reactive components, ambient air, as well as biologic tissue - typically also incorporating fluids - results in a complex system. Thus, real progress in plasma-medicine requires a profound knowledge of species, their fluxes and processes hitting biological tissues. That will allow in particular the necessary tailoring of the discharge to fit the conditions. The complexity of the problem can only be overcome by a common effort of many groups and requires a comparison of their results. A reference device based on the already well-investigated micro-scaled atmospheric pressure plasma jet is presented. It is developed in the frame of the European COST initiative MP1101 to establish a publicly available, stable and reproducible source, where required plasma conditions can be investigated. Here we present the design and the ideas behind. The presentation discusses the requirements for the reference source and operation conditions. Biological references are also defined by the initiative. A specific part of the talk will be attributed to the reproducibility of results from various samples of the device.

*Funding by the DFG within the Package Project PAK816 "Plasma Cell Interaction in Dermatology" and the Research Unit FOR 1123 "Physics of microplasmas" is gratefully acknowledged.

Contributed Papers

8:30

NR1 2 Development challenges for Low Temperature Plasma Sources "from Idea to Prototype"* T. GERLING, J.-S. BAUDLER, S. HORN, M. SCHMIDT, K.-D. WELTMANN, *INP Greifswald* While plasma medicine is a well-motivated and intensively investigated topic, the requirements on the plasma sources change for individual applications. For example in dermatology, a large scale treatment is favored, while in dentistry, a localized application of plasma sources is required. Meanwhile, plasma source development is based on feasibility and not on the application. When a source is developed, it is usually motivated towards an application instead of considering an application and designing a plasma source to fit its needs. Each approach has its advantage and can lead to an advance in the field. With this contribution, we will present an approach from idea to prototype and show challenges in the plasma source development. For example, the consideration of legal regulations, adaption of the plasma source for a specific field of application and the interplay of gas flow dynamics with electrical field distribution. The solution was developed within several iterations to optimize it for different requirements. The obstacles that occurred during the development process will be highlighted and discussed. Afterwards the final source is characterized for a potential medical application and compared directly with a plasma source certified as a medical product.

*Acknowledging grants: AU 11 038; ESF/IV-BM-B35-0010/13.

8:45

NR1 3 Experimental and numerical study on the dynamics of a μs helium plasma gun discharge with various amounts of N_2 admixture* ANNE BOURDON, *LPP, Ecole Polytechnique, France* THIBAULT DARNY, ERIC ROBERT, *GREMI, Orleans, France* FRANCOIS PECHEREAU, *CERFACS, Toulouse, France* PEDRO VIEGAS, *LPP, Ecole Polytechnique, France* JEAN-MICHEL POUVESLE, *GREMI, Orleans, France* These last years, atmospheric pressure plasma jets formed by pulsed helium discharges ignited in thin dielectric tubes have been extensively studied due to their potential for biomedical applications. So far, most experiments have been dedicated to the study of the plasma plume. For endoscopic treatments, it is also important to better understand and optimize the propagation of discharges in long dielectric tubes as catheters. First we present an experimental and numerical study on the dynamics of a μs helium plasma discharge with N_2 admixture in a long dielectric tube. We compare the velocity of the discharge front for various amounts of N_2 and different applied voltages and show a good agreement between experiments and simulations. Second, we compare time-resolved measurements and simulations of longitudinal and radial electric fields associated with plasma propagation in the dielectric tube and in the plasma plume. It is interesting to note that measurements obtained with a probe located outside the dielectric tube are in excellent agreement with simulations. This allows to infer from simulations the time evolution of the electric field on the discharge axis which is a key parameter for applications.

*The authors acknowledge the computational resources of the Mesocentre of Ecole Centrale Paris.

Invited Papers

9:00
NR1 4 Dynamics of filamentary plasma jets used in plasma medicine*
STEPHAN REUTER, *INP Greifswald e.V.*

Atmospheric plasmas exhibit large gradients in space and time. This challenges diagnostics such as LIF or other quantitative species detection methods. Single shot and 2D measurements can supply information otherwise hidden in averaging single point measurements. Especially the interaction of jet like plasmas with ambient surroundings poses unmet challenges. In the present work, several approaches of laser diagnostics of plasma and gas phase combined with numerical simulation sow how a careful study of the plasma initiated processes can lead to an at least partial understanding of plasma interaction with liquid and biological systems. In collaboration with Ansgar Schmidt-Bleker, INP Greifswald e.V.; Sylvain Iseni, GREMI, UMR 7344, CNRS/Université d'Orléans; and Jörn Winter, Helena Jablonowski, and Klaus-Dieter Weltmann, INP Greifswald e.V.

*BMBF FKZ 03Z2DN12.

SESSION NR2: PLASMA CVD/RADICAL ASSISTED CVD
Thursday Morning, 15 October 2015
Room: 308 AB at 8:00
Kazunori Koga, Kyushu University, presiding

Contributed Papers

8:00
NR2 1 Spectroscopic studies of MW plasmas containing HMDSO, O_2 and N_2* ANDY NAVE, JUERGEN ROEPCKE, *INP-Greifswald, Germany* FELIX MITSCHKER, PETER AWAKOWICZ, *Ruhr University Bochum, Germany* The deposition of SiO_x layers based on organosilicon plasmas is used to implement advantageous mechanical, electrical, and/or optical properties on various substrates. The development of such coating processes resulting in a wide range of chemical and physical film properties, using hexamethyldisiloxane (HMDSO) as a precursor, has been in the center of interest of various studies. In plasma, the dissociation of HMDSO into a large amount of fragments is a complex chemical phenomenon. The monitoring of the precursor and of formed species is very valuable to understand the plasma chemistry. Infrared absorption spectroscopy based on lead salt lasers and EC Quantum Cascade Laser have been used to monitor the concentrations of HMDSO, and of the reaction products CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2 and CH_3 as a function of the HMDSO/O_2 mixture ratio, and the power at various pressures in a MW plasma deposition reactor. Optical emission spectroscopy has been applied as complementary diagnostics to evaluate electron density and electron temperature.

*Supported by the German Research Foundation within SFB-TR24 and SFB-TR87.

8:15
NR2 2 Study of O_3-TEOS SiO_2 Cladding for Silicon Photonics Devices KEIZO KINOSHITA, *PETRA* TSUYOSHI HORIKAWA, *PETRA, AIST* DAISUKE SHIMURA, HIROYUKI TAKAHASHI, TOHRU MOGAMI, *PETRA* Silicon Photonics (SiPh) is a promising technology for large-capacity and wide-band data communications for the distance from millimeter to 100 meters which corresponded well to data center applications. This paper describes about O_3-TEOS SiO_2 film developments as an upper cladding over Si waveguide core fabricated on silicon-on-insulator wafers. It was compared with a plasma-enhanced chemical-vapor-deposition (PE-CVD) SiO_2 film used widely as the cladding material. The O_3-TEOS SiO_2 showed very high gap-fill characteristic at parallel arrangement of two waveguides. However, its propagation loss was 1.83 dB/cm which is three times larger than that of the conventional PE-CVD SiO_2 cladding. Chemical analyses by FT-IR and TDS for these two types of cladding films were carried out to clarify this reason. It was clearly shown that remained water within the O_3-TEOS SiO_2 cladding could cause the larger propagation loss by O-H stretching absorption. The water exclusion procedure should be developed to apply O_3-TEOS SiO_2 for the cladding materials. This work was supported by NEDO.

8:30
NR2 3 Low temperature synthesis of silicon nitride thin films deposited by VHF/RF PECVD for gas barrier application JUN S. LEE, KYUNG S. SHIN, B.B. SAHU, JEON G. HAN,* *NU-SKKU Joint Institute for Plasma Nano Materials (IPNM), Center for Advanced Plasma Surface Technology (CAPST) and Sungkyunkwan University* In this work, silicon nitride (SiNx) thin films were deposited on polyethylene terephthalate (PET) substrates as barrier layers by plasma enhanced chemical vapor deposition (PECVD) system. Utilizing a combination of very high-frequency (VHF 40.68 MHz) and radio-frequency (RF 13.56 MHz) plasmas it was possible to adopt PECVD deposition at low-temperature using the precursors: Hexamethyldisilazane (HMDSN) and nitrogen. To investigate relationship between film properties and plasma properties, plasma diagnostic using optical emission spectroscopy (OES) was performed along with the film analysis using Fourier transform infrared spectroscopy (FT-IR) and X-ray photoelectron spectroscopy (XPS). OES measurements show that there is dominance of the excited N2 and N2+ emissions with increase in N2 dilution, which has a significant impact on the film properties. It was seen that all the deposited films contains mainly silicon nitride with a small content of carbon and no signature of oxygen. Interestingly, upon air exposure, films have shown the formation of Si-O bonds in addition to the Si-N bonds. Measurements and analysis reveals that SiNx films deposited with high content of nitrogen with HMDSN plasma can have lower gas barrier properties as low as 7.3×10^{-3} g/m2/day.

*Also at Chiang Mai University.

8:45
NR2 4 Development of high-density radical source and its application to high-speed growth of nitride semiconductors by plasma-assisted molecular beam epitaxy HIROKI KONDO, *Nagoya University* YUKINORI KIHEIDA, HIROYUKI KANO, *NU EcoEngineering Co. Ltd.* YVON CORDIER, *CNRS-CRHEA* PHANNARA AING, OLIVIER GRANGE, *Riber Co.* YURI TSUTSUMI, OSAMU ODA, MASARU HORI, HIROSHI AMANO,

THURSDAY MORNING \ NR2

Nagoya University The high-density radical source (HDRS) was developed to improve growth characteristics of plasma-assisted molecular beam epitaxy (PA-MBE) and its film qualities. The growth rate of GaN and InGaN by the PA-MBE is generally much lower than that by a conventional metal organic vapor phase epitaxy (MOVPE). To improve the growth rate of PA-MBE, we have developed the HDRS, which can realize a nitrogen radical density up to 3×10^{12} cm^{-3}. Then, a faster growth rate of 2.5μm/h in GaN homoepitaxy have been performed employing the HDRS. The growth rate of InGaN was also enhanced by this method. In general, mosaicity of the epilayer confirmed using the X-ray omega rocking curve (XRC) increased with increasing In content in the case using the ICP. However, that by the HDRS hardly changed even at the In content of 16%. Incorporation of impurity was also suppressed according to secondary ion mass spectrometry (SIMS) results. Fine and uniform photoluminescence emission was also confirmed at the whole region of substrates. These results indicate high potential of the HDRS to realize the high-rate growth of high quality and high-In content InGaN.

9:00

NR2 5 Reactive radical production and transport analysis in ammonia-hydrogen-argon microwave plasmas TOSHIHIKO IWAO, *Tokyo Electron Limited* PETER VENTZEK, *Tokyo Electron America* ROCHAN UPADHYAY, *Esgee Technologies Inc.* LAXMINARAYAN RAJA, *University of Texas Austin* KIYOTAKA ISHIBASHI, *Tokyo Electron Limited* High quality conformal dielectric films are playing an ever increasing role in advanced semiconductor device and memory manufacturing. Plasma-enhanced atomic layer deposition (PEALD) meet both quality and throughput requirements. For dielectric film PEALD, the attributes of microwave plasmas are important for the prevention of wafer device damage that occurs when other plasmas are used. With its advantages, PEALD brings with it complexity. In this presentation we present the results from an investigation of radical species generation and transport phenomena using "VizGlow" [1] a multi-dimensional plasma simulation tool. In the computational model, the ammonia, hydrogen, and argon mixture plasma chemistry for silicon nitride deposition is based on work by Arakoni *et al.* [2]. From our investigation we are able to show the important role radical-ion chemistry plays and relate these results to basic process properties.

[1]"VizGlow: Plasma Modeling Software for Multi-Dimensional Simulations of Non-Equilibrium Glow Discharge Systems" Theory Manual, version 2.1, Esgee Technologies Inc.
[2]Arakoni *et al.*, J. Phys. D: Appl. Phys. **40**, 2476 (2007).

9:15

NR2 6 Plasma CVD synthesis of new diamond-bismuth thin films by solid-source immersion TAKAHIRO TAMURA, *Faculty of Engineering, Hokkaido University* Doping various elements to carbon is gathering much attention recently. In particular, doping to diamond is attractive for various applications, but it is extremely difficult except for a very few numbers of elements (e.g. N, P and B). Since the search for dopants and their combinations is still underway, a simple and versatile technique for the doping to the diamond has been awaited. We have developed a new method for the doping to diamond, which is simply immersing a solid source in the CVD plasma. We used this technique to examine the possibility to dope bismuth to the diamond. It was necessary to make a device to let bismuth seep into the CVD plasma because of its low melting temperature. The grown samples were characterized by X-ray fluorescence, X-ray diffraction, Raman spectroscopy, TEM, XPS and electrochemical cyclic voltammetry. We found nanoparticles of an unusual carbon allotrope (Chaoite) at grain boundaries of diamond microcrystals. Most of the bismuth was included among the nanoparticles. Molecule-like Raman spectra were observed from the film, which suggests the existence of various carbon nanostructures.

SESSION NR3: PLASMA SHEATHS AND BOUNDARY LAYERS
Thursday Morning, 15 October 2015; Room: 305 AB at 8:00; Steven Shannon, North Carolina State University, presiding

Invited Papers

8:00

NR3 1 The interaction of the near-field plasma with antennas used in magnetic fusion research*
JOHN CAUGHMAN, *Oak Ridge National Laboratory*

Plasma heating and current drive using antennas in the Ion Cyclotron Range of Frequencies (ICRF) are important elements for the success of magnetic fusion. The antennas must operate in a harsh environment, where local plasma densities can be $>10^{18}/m^3$, magnetic fields can range from 0.2-5 Tesla, and antenna operating voltages can be >40 kV. This environment creates operational issues due to the interaction of the near-field of the antenna with the local plasma. In addition to parasitic losses in this plasma region, voltage and current distributions on the antenna structure lead to the formation of high electric fields and RF plasma sheaths, which can lead to enhanced particle and energy fluxes on the antenna and on surfaces intersected by magnetic field lines connected to or passing near the antenna. These issues are being studied using a simple electrode structure and a single-strap antenna on the Prototype Materials Plasma EXperiment (Proto-MPEX) at ORNL, which is a linear plasma device that uses an electron Bernstein wave heated helicon plasma source to create a high-density plasma suitable for use in a plasma-material interaction test stand. Several diagnostics are being used to characterize the near-field interactions, including double-Langmuir probes, a retarding field energy analyzer, and optical emission spectroscopy. The RF electric field is being studied utilizing Dynamic Stark Effect spectroscopy and Doppler-Free Saturation Spectroscopy. Recent experimental results and future plans will be presented.

*ORNL is managed by UT-Battelle, LLC, for the U.S. DOE under Contract DE-AC-05-00OR22725.

Contributed Papers

8:30

NR3 2 Ion velocities in an electronegative presheath MARK SOBOLEWSKI, YICHENG WANG, AMANDA GOYETTE, *National Institute of Standards and Technology* Under certain conditions in radio-frequency (rf) discharges, features in ion energy distributions (IEDs) measured at an electrode depend very sensitively on ion velocities far upstream, in the presheath. By measuring such distributions together with sheath voltage waveforms, presheath ion velocities can be determined and long-standing controversies regarding presheath transport can be resolved. For rf-biased, inductively coupled plasmas in CF_4 gas, we determined the presheath velocities of all significant positive ions. Velocities were significantly lower than those predicted by electropositive models. These results contradict the claim that negative ions are confined to a core electronegative plasma surrounded by an electropositive peripheral plasma and presheath. Also, they indicate that models that neglect the effect of negative ions in presheaths will under certain conditions yield dramatically inaccurate predictions for IEDs, average ion energy, and rf bias power.

8:45

NR3 3 Bulk plasma effects of the electron sheath* BENJAMIN YEE, *Sandia Natl Labs* BRETT SCHEINER, *University of Iowa* MATT HOPKINS, EDWARD BARNAT, *Sandia Natl Labs* SCOTT BAALRUD, *University of Iowa* Electron sheaths are commonly found around relatively small, positively biased boundaries. Conventional analysis treats these structures as local phenomena with little impact on the bulk plasma. We present a theoretical treatment of the electron sheath that suggests an extensive presheath region, many times larger than that of an analagous ion sheath. We also find that the electrons must flow into the electron sheath with a minimum flow speed, which can be considered an electron sheath equivalent of the Bohm criterion. Two-dimensional particle-in-cell simulations are presented, demonstrating the existence of this electron presheath and a global flow of electrons to the positive boundary. Velocity distributions reveal that electron flux across the sheath edge is not random thermal flux, but a Maxwellian electron distribution flow-shifted to meet the minimum flow speed at the sheath edge. Qualitative agreement is found between the density distribution of electrons in simulations when compared to LCIF measurements of a thermionic plasma.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contracts DE-AC04-94SL85000 and DE-SC0001939.

9:00

NR3 4 The characteristics of RF modulated plasma boundary sheaths: An analysis of the standard sheath model* SCHABNAM NAGGARY, RALF PETER BRINKMANN, *Ruhr University Bochum* The characteristics of radio frequency (RF) modulated plasma boundary sheaths are studied on the basis of the so-called "standard sheath model." This model assumes that the applied radio frequency ω_{RF} is larger than the plasma frequency of the ions but smaller than that of the electrons. It comprises a phase-averaged ion model – consisting of an equation of continuity (with ionization neglected) and an equation of motion (with collisional ion-neutral interaction taken into account) – a phase-resolved electron model – consisting of an equation of continuity and the assumption of Boltzmann equilibrium –, and Poisson's equation for the electrical field. Previous investigations have studied the standard sheath model under additional approximations, most notably the assumption of a step-like electron front [1]. This contribution presents an investigation and parameter study of the standard sheath model which avoids any further assumptions. The resulting density profiles and overall charge-voltage characteristics are compared with those of the step-model based theories.

*The authors gratefully acknowledge Efe Kemaneci for helpful comments and fruitful discussions.

[1] V. A. Godyak and Z. K. Ghanna, Sov. J. Plasma Phys. **6**, 372 (1979).

9:15

NR3 5 Theory of the Electron Sheath and Presheath* BRETT SCHEINER, SCOTT BAALRUD, *University of Iowa* BENJAMIN YEE, MATTHEW HOPKINS, EDWARD BARNAT, *Sandia National Laboratories* Electron sheaths are commonly found near Langmuir probes collecting the electron saturation current. The common assumption is that the probe collects the random flux of electrons incident on the sheath, which tacitly implies that there is no electron presheath and that the flux collected is due to a velocity space truncation of the velocity distribution function (VDF). This work provides a dedicated theory of electron sheaths, which suggests that electron sheaths are not so simple. Motivated by VDFs observed in recent Particle-In-Cell (PIC) simulations, we develop a 1D model for the electron sheath and presheath. In the model, under low temperature plasma conditions, an electron pressure gradient accelerates electrons in the presheath to a flow velocity that exceeds the electron thermal speed at the sheath edge. This pressure gradient allows the generation of large flows compared to those that would be generated by the electric field alone. It is due to this pressure gradient that the electron presheath extends much further into the plasma (nominally by a factor of $\sqrt{m_i/m_e}$) than an analogous ion presheath. Results of the model are compared with PIC simulations.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under contract DE-AC04-94SL85000 and by the Office of Science Graduate Student Research (SCGSR) program under Contract Number DE-AC05-06OR23100.

9:30

NR3 6 Virtual Cathodes near small electrodes biased near the plasma potential and its effects on Langmuir probes* CHI-SHUNG YIP, NOAH HERSHKOWITZ, *University of Wisconsin - Madison* GREG SEVERN, *University of San Diego* Movable small (3cm x 3.8cm) plates biased near the plasma potential are immersed in a filament discharge in a multi-dipole chamber. The plates are small ($A_{plate}/A_{chamber} < (m_e/M_i)^{1/2}$) [1] such that an electron sheath is possible. Plasma potential and IVDF's near the plate are measured, and virtual cathodes, a double layer consists of an ion sheath and an electron sheath, was found to form. Ion velocities are determined by Laser-Induced Florescence, the electron temperature and electron density are measured by a planar Langmuir probe and the plasma potential is measured by an emissive probe. Effects of the virtual cathode on Langmuir probe I-V characteristics were predicted through estimating the current collection of an electrode in the presence of the virtual cathode, and was experimentally investigated by comparing I-V characteristics of the small plate and a 0.6cm diameter Langmuir probe.

*This work is supported by U.S. DOE under the Grant and Contract No. DE-FG02-97ER54437.

[1] S. D. Baalrud, N. Hershkowitz, and B. Longmier, Phys. Plasmas **14**, 042109 (2007).

SESSION NR4: PLASMA-ASSISTED COMBUSTION
Thursday Morning, 15 October 2015
Room: 303 AB at 8:00
Shinji Kambara, Gifu University, presiding

Contributed Papers

8:00

NR4 1 Nanosecond-gated laser induced breakdown spectroscopy in hydrocarbon mixtures KAZUNOBU KOBAYASHI, *Osaka Gas Co., Ltd., University of Notre Dame* MOON SOO BAK, *Sungkyunkwan University* HIROKI TANAKA, *Osaka Gas Co., Ltd.* HYUNGROK DO, *Seoul National University, University of Notre Dame* Nanosecond-gated laser induced breakdown spectroscopy have been carried out in four different hydrocarbon gas mixtures (CH4/CO2/O2/N2, C2H4/O2/N2, C3H8/CO2/O2/N2 and C4H10/CO2/O2/N2) to investigate the effect of gas species on the laser induced breakdown kinetics and resulting the plasma emission. For this purpose, each mixture that consists of different species has the same atom composition. It is found that the temporal emission spectra and the decay rates of atomic line-intensities are almost identical for the breakdowns in the four different mixtures. This finding may indicate that the breakdown plasmas of these mixtures reach a similar thermodynamic and physiochemical state after its formation, resulting in a similar trend of quenching of excited species.

8:15

NR4 2 Response of a laminar M-shaped premixed flame to plasma forcing DEANNA A. LACOSTE, *King Abdullah University of Science and Technology* JONAS P. MOECK, *Technische Universität Berlin* MIN SUK CHA, SUK HO CHUNG, *King Abdullah University of Science and Technology* DRACO COLLABORATION We report on the response of a lean methane-air flame to non-thermal plasma forcing. The set-up consists of an axisymmetric burner, with a nozzle made of a quartz tube of 7-mm inlet diameter. The equivalence ratio is 0.9 and the flame is stabilized in an M-shape morphology over a central stainless steel rod and the quartz tube. The plasma is produced by nanosecond pulses of 10 kV maximum voltage amplitude, applied at 10 kHz. The central rod is used as a cathode, while the anode is a stainless steel ring, fixed on the outer surface of the quartz tube. The plasma forcing is produced by bursts of plasma pulses of 1 s duration. The response of the flame is investigated through the heat release rate (HRR) fluctuations. The chemiluminescence of CH* between two consecutive pulses was recorded using an intensified camera with an optical filter to estimate the HRR fluctuations. The results show that, even though the plasma is located in the combustion area, the flame is not responding to each single plasma pulse, but is affected by the discharge burst. The plasma forcing can then be considered as a step of forcing: the beginning of a positive step corresponding to the first plasma pulse, and the beginning of a negative step corresponding to the end of the last pulse of the burst. The effects of both positive and negative steps were investigated. The response of the flame is then analyzed and viable mechanisms are discussed.

8:30

NR4 3 Characteristics of 2-heptanone decomposition using nanosecond pulsed discharge plasma YUKI NAKASE, YUICHI FUKUCHI, DOUYAN WANG, TAKAO NAMIHIRA, HIDENORI AKIYAMA, *Kumamoto University* KUMAMOTO UNIVERSITY COLLABORATION Volatile organic compounds (VOC) evaporate at room temperature. VOCs typically consist of toluene, benzene and ethyl acetate, which are used in cosmetics, dry cleaning products and paints. Exposure to elevated levels of VOCs may cause headaches, dizziness and irritation to the eyes, nose, and throat; they may also cause environmental problems such as air pollution, acid rain and photochemical smog. As such, they require prompt removal. Nanosecond pulsed discharge is a kind of non-thermal plasma consisting of a streamer discharge. Several advantages of nanosecond pulsed discharge plasma have been demonstrated by studies of our research group, including low heat loss, highly energetic electron generation, and the production of highly active radicals. These advantages have shown ns pulsed discharge plasma capable of higher energy efficiency for processes, such as air purification, wastewater treatment and ozone generation. In this research, nanosecond pulsed discharge plasma was employed to treat 2-heptanone, which is a volatile organic compound type and presents several harmful effects. Characteristics of treatment dependent on applied voltage, gas flow rate and input energy density were investigated. Furthermore, byproducts generated by treatment were also investigated.

8:45

NR4 4 Importance of atomic oxygen in preheating zone in plasma-assisted combustion of a steady-state premixed burner flame K. ZAIMA, *Hokkaido University, Japan* H. AKASHI, *National Defense Academy, Japan* K. SASAKI, *Hokkaido University, Japan* It is widely believed that electron impact processes play essential roles in plasma-assisted combustion. However, the concrete roles of high-energy electrons have not been fully understood yet. In this work, we examined the density of atomic oxygen in a premixed burner flame with the superposition of dielectric barrier discharge (DBD). The density of atomic oxygen in the reaction zone was not affected by the superposition of DBD, indicating that the amount of atomic oxygen produced by combustion reactions was much larger than that produced by electron impact processes. On the other hand, in the preheating zone, we observed high-frequency oscillation of the density of atomic oxygen at the timings of the pulsed current of DBD. The oscillation suggests the rapid consumption of additional atomic oxygen by combustion reactions. A numerical simulation using Chemkin indicates the shortened ignition delay time when adding additional atomic oxygen in the period of low-temperature oxidation. The present results reveals the importance of atomic oxygen, which is produced by the effect of high-energy electrons, in the preheating zone in plasma-assisted combustion of the steady-state premixed burner flame.

9:00

NR4 5 Plasma Torch for Plasma Ignition and Combustion of Coal ALEXANDR USTIMENKO, *R&D Plasmotechnics* VLADIMIR MESSERLE, *Retired* Plasma-fuel systems (PFS) have been developed to improve coal combustion efficiency. PFS is a pulverized coal burner equipped with arc plasma torch producing high temperature air stream of 4000 – 6000 K. Plasma activation of coal at the PFS increases the coal reactivity and provides more effective ignition and ecologically friendly incineration of low-rank coal. The main and crucial element of PFS is plasma torch. Simplicity and reliability of the industrial arc plasma torches using cylindrical copper cathode and air as plasma forming gas predestined their application at heat and power engineering for plasma aided coal combustion. Life time of these plasma torches electrodes is critical and usually limited to 200 hours. Considered in this report direct current arc plasma torch has the cathode life significantly exceeded 1000 hours. To ensure the electrodes long life the process of hydrocarbon gas dissociation in the electric arc discharge is used. In accordance to this method atoms and ions of carbon from near-electrode plasma deposit on the active surface of the electrodes and form electrode carbon condensate which operates as "actual" electrode. Complex physicochemical investigation showed that deposit consists of nanocarbon material.

SESSION OR1: PLASMA INTERACTION WITH LIQUIDS I
Thursday Morning, 15 October 2015
Room: 301 B at 10:00
Fumiyoshi Tochikubo, Tokyo Metropolitan University, presiding

Contributed Papers

10:00
OR1 1 Production of water mist from electrolyte surface in contact with atmospheric-pressure dc helium glow plasma K. SASAKI, H. ISHIGAME, S. NISHIYAMA, *Hokkaido University, Japan* Plasma-liquid interaction is a new subject which has been opened by developments of atmospheric-pressure plasma sources. In this work, we adopted laser Mie scattering to examine an atmospheric-pressure dc helium glow plasma in contact with NaCl solution. The plasma was produced by applying a dc voltage between a stainless-steel gas nozzle and the electrolyte via a register of 100 kΩ. The gap distance between the electrolyte surface and the electrode was 4 mm. Helium as a working gas was fed from the nozzle toward the electrolyte surface. The discharge space was illuminated using a cw laser beam at a wavelength of 457 nm, and the scattered laser light was captured using a high-speed camera with an image intensifier via an interference filter at the laser wavelength. The scattered laser light told us the existence of particulates or water mists in the discharge space. The water mists were produced from the electrolyte surface explosively as well as randomly. The trajectories of the mists were basically parabolic. We sometimes observed the expansion of the mist size in the gas phase. The expansion was followed by the disappearance of the mist. This may be due to the evaporation of the mist, and is considered to be the production mechanism of Na in the gas phase.

10:15
OR1 2 Precision charging of microparticles in plasma via the Rayleigh instability for evaporating charged liquid droplets* EUAN BENNET, *University of Glasgow* CHARLES M.O. MAHONY, *Ulster University* HUGH E. POTTS, PAUL EVEREST, *University of Glasgow* DAVID RUTHERFORD, SADEGH ASKARI, COLIN KELSEY, FATIMA PEREZ-MARTIN, NEIL HAMILTON, DAVID A. MCDOWELL, DAVIDE MARIOTTI, PAUL MAGUIRE, *Ulster University* DECLAN A. DIVER, *University of Glasgow* In this paper we describe a novel method for delivering a precise, known amount of electric charge to a micron-sized solid target. Aerosolised microparticles passed through a plasma discharge will acquire significant electric charge. The fluid stability under evaporative stress is a key aspect that is core to the research. Initially stable charged aerosols subject to evaporation (i.e. a continually changing radius) may encounter the Rayleigh stability limit. This limit arises from the electrostatic and surface tension forces and determines the maximum charge a stable droplet can retain, as a function of radius. We demonstrate that even if the droplet charge is initially much less than the Rayleigh limit, the stability limit will be encountered as the droplet evaporates. The instability emission mechanism is strongly linked to the final charge deposited on the target, providing a mechanism that can be used to ensure a predictable charge deposit on a known encapsulated microparticle.

*The authors gratefully acknowledge support from EPSRC via Grant Numbers EP/K006142/1 and EP/K006088/1.

10:30
OR1 3 Controlled Microdroplet Transport & Charging in an Atmospheric Pressure Microplasma* COLIN KELSEY, PAUL MAGUIRE, CHARLES MAHONY, NEIL HAMILTON, DAVIDE MARIOTTI, DAVID RUTHERFORD, DAVID MCDOWELL, FÁTIMA PÉREZ-MARTÍN, *Ulster University* EUAN BENNET, HUGH POTTS, DECLAN DIVER, *University of Glasgow* ULSTER UNIVERSITY COLLABORATION, UNIVERSITY OF GLASGOW COLLABORATION We have measured charge and evaporation rates of a stream of micron-scale H_2O droplets transported through a low-temperature helium-neon rf plasma. N_e and T_e, estimated from plasma impedance, were $\sim 10^{13}/cm^3$ and $\sim$5 eV respectively; gas temperature, from N_2 spectroscopy, was <400 K. With a log-normal aerosol droplet size distribution, 15 micron CMD and droplet velocity distribution within a parabolic envelope of $\sim$75% of the local gas speed, the plasma induced evaporation caused an average diameter reduction of <2 microns. This is equivalent to an average evaporation rate $\sim$ 2 orders of magnitude higher than reported for similar droplets in a comparable gas flow without plasma. Using charged droplet collection and current amplification, we have measured sub-millisecond charge pulses of up to 10^7e from a droplet stream with $\sim 2.5 \times 10^3$ droplets/s demonstrating the transport of droplets beyond the plasma and recombination region with negative charge retained. Time averaged measurements using an alternative technique show the mean charge per droplet is $\sim 10^5$e. Results from an enhanced resolution charge measurement apparatus, currently being tested and using individual and size selectable droplets will be reported.

*EPSRC funded

[1]P. Maguire *et al.*, Appl. Phys. Lett. **106**, 224101 (2015).

10:45
OR1 4 Bubble Phenomena caused by High Repetitive Plasmas in Water MASAHIRO AKIYAMA, TAKUMA OIKAWA, MASATOSHI FUE, RYOMA OGATA, KOICH TAKAKI, *Iwate Univ* HIDENORI AKIYAMA, *Kumamoto Univ* IWATE UNIV TEAM, KUMAMOTO UNIV COLLABORATION Streamer discharges in water were generated by a pulsed power generator. The streamer shape changed depending on pulse repetition rate. Streamer discharges at 500 pulses per second (pps) resulted in a ball shape. Under this formation, small bubbles gather near the electrode tip. Our aims are the analysis and discussion of the bubble phenomena caused by high repetitive plasmas produced in water. Pulsed power with a maximum output of 1 J/pulse was applied to an electrode of 0.8 mm in diameter covered by an insulator of 2 mm thickness. The electrode was inserted into tap water with conductivity of 170 uS/cm. The polarity was positive. Phenomena, in which the resulting gas bubbles oscillate and gather, were found to have an important role in producing ball shape streamer discharges.

11:00
OR1 5 The Time Evolution of Streamer Discharges in Single and Multiple Bubbles in Water* SELMAN MUJOVIC, JOSEPH GROELE, JOHN FOSTER, *University of Michigan* The interaction of plasma with liquid water lies at the heart of a variety of revisited technological applications ranging from water treatment to wound healing. Plasma ignition and propagation in water, however, is poorly understood. It has been theorized that plasma streamer

propagation takes place in microbubbles, namely streamer bubble hopping. In this work, discharge development in single and multiple bubble acoustic systems is investigated using high-speed imaging and emission spectroscopy. Optical filters allow for time resolved measurements of specific chemical species as well. Better understanding of these breakdown processes will guide the construction of an effective plasma water purifier.

*NSF CBET 1336375.

11:15
OR1 6 Multi-physics study of plasma in liquids: The case of Plasma Electrolytic Oxidation (PEO) ALEXANDRE NOMINE,* *Institut Jean Lamour - CNRS - Universite de Lorraine* SAM TROUGHTON, *University of Cambridge* ANNA NOMINE,† GERARD HENRION, *Institut Jean Lamour - CNRS - Universite de Lorraine* BILL CLYNE, *University of Cambridge* PEO is a promising technique in order to grow rapidly oxide coatings with high corrosion and wear resistance. Oxidation is driven by millions of simultaneous micro-discharges (MD) that occur at the interface between the substrate and the liquid electrolyte. However, the mechanisms of breakdown and the subsequent oxidation are not well understood yet. Current profiles and Ultra-Fast Imaging of single discharges allows to correlate the size and life-time of the discharge with different electric parameters (Q, Imax). MD are found to appear in cascade, switching on and off with a frequency in the order of 1–10 kHz. Formation of a bubble is observed directly after the ignition of the discharge. The growth rate that varies between 1 and 10 m/s, is used to estimate the gas pressure in the bubble. The influence of the pulse frequency on the bubble shape and on the coatings will be presented. MD size and life time are known to increase with coating thickness presumably due to higher charge accumulation. This study shows that ms scale, the evolution of MD size and life time evaluates similarly, suggesting that the coating thickness is not the only parameter governing the MD size and life-time.

*second affiliation: The Open University.
†second affiliation: The Open University.

11:30
OR1 7 Optical Emission Spectroscopy of Microplasma Discharge in Sea Water* VLADISLAV GAMALEEV, AKIMITSU HATTA, HIROSHI FURUTA, JUN-SEOK OH, YO OKAMURA, KENSUKE KITAMURA, YUSUKE HASHIMOTO, *Kochi University of Technology* We have been investigating microplasma discharge in sea water for optical emission spectroscopy. Microplasma discharge in artificial sea water (10ASW) was carried using needle-to-plane platinum electrode system. The gap, between electrodes, was ranged from 10 to 60 microns. The electricity source was impulse generatorwith MOSFET switch and variable capacitance and inductance. The maximum voltage and current for this scheme were respectively 1 kV and 10 A, pulse width 10 μs. It has been confirmed that, using the micro-gap configuration, spark discharges were ignited at the conventional breakdown voltages below 1kV, even in the conductive sea water. Was noted formation of small bubbles before of the plasma ignition process. The mechanism of formation of these bubbles is mostly Joule heating because of high currents. It has been speculated that plasma discharge initiates in bubbles. Optical emission spectroscopy of microplasma in sea water was carried. In the spectra, emission peaks for H, O, Na, Mg, Ca, Cl and Pt were clearly detected. Besides the main components of 10ASW, contaminants from the electrodes appeared in the spectra. The characteristics of microplasma discharge in sea water and analysis of the optical emission spectra will be presented.

*This work was supported by JSPS KAKENHI Grant Number 26600129. The ASW was provided from Prof. Kei Okamura of Kochi University.

11:45
OR1 8 Simulation of plasma discharge in liquids: A detailed two-phase fluid approach ALI CHARCHI AGHDAM, TANVIR FAROUK, *University of South Carolina* REACTING SYSTEMS AND ADVANCED ENERGY RESEARCH LABORATORY TEAM Plasma discharge in liquids has gained great attention recently due to its applications in biomedical engineering, fuel processing, and water treatment and so on. Despite the tremendous interest, a comprehensive understanding of the underlying physics still remains limited. In the current work, an attempt is made to present a mathematical multi-physics model to describe the discharge of plasma in liquids. An in-house modeling platform is developed for simulating plasma formation in multiphase fluids. The model resolves a detailed two-phase fluid including viscous effects, surface tension, gravitational forces and electrical body force. All the governing equations are solved for gas and liquid phases. Electric field and charged species equations along with the plasma reaction kinetics are solved to get the charge distribution in the different phases as well as at the gas-liquid interface to obtain the electric body force acting at the interface. By coupling the above sub-models, a comprehensive multi-physics model for plasma discharge in liquids is constructed which is able to capture several physical aspects of the phenomena especially the role of the bubble, its motion and distortion on plasma characteristics.

SESSION OR2: PLASMA ETCHING I
Thursday Morning, 15 October 2015; Room: 308 AB at 10:00; Michael Liberman, University of California Berkeley, presiding

Invited Papers

10:00
OR2 1 In-Plasma Photo-Assisted Etching*
DEMETRE ECONOMOU, *University of Houston*

A methodology to precisely control the ion energy distribution (IED) on a substrate allowed the study of silicon etching as a function of ion energy at near-threshold energies. Surprisingly, a substantial etching rate was observed, independent of ion energy, when the ion energy was below the ion-assisted etching threshold (~ 16 eV for etching silicon with chlorine plasma). Careful experiments led to the conclusion that this "sub-threshold" etching was due to photons, predominately at wavelengths <1700 Å. Among the plasmas investigated, photo-assisted etching (PAE) was lowest in Br_2/Ar gas mixtures and highest in $HBr/Cl_2/Ar$. Above threshold etching rates scaled with the square root of ion energy. PAE rates scaled with the product of surface halogen coverage (measured by X-ray photoelectron spectroscopy) and Ar emission intensity (7504 Å). Scanning electron and atomic force microscopy (SEM and AFM) revealed that photo-etched surfaces were very rough, quite likely due to the inability of the photo-assisted process to remove contaminants from the surface. In-plasma PAE may be be a complicating factor for processes that require low ion energies, such as atomic layer etching. On the other hand PAE could produce sub-10 nm high aspect ratio (6:1) features by highly selective plasma etching to transfer nascent nanopatterns in silicon.

*Work supported by DOE Plasma Science Center and NSF.

10:30

OR2 2 Advanced Simulation Technology to Design Etching Process on CMOS Devices*

NOBUYUKI KUBOI, *Sony Corporation*

Prediction and control of plasma-induced damage is needed to mass-produce high performance CMOS devices. In particular, side-wall (SW) etching with low damage is a key process for the next generation of MOSFETs and FinFETs. To predict and control the damage, we have developed a SiN etching simulation technique for $CH_xF_y/Ar/O_2$ plasma processes using a three-dimensional (3D) voxel model. This model includes new concepts for the gas transportation in the pattern, detailed surface reactions on the SiN reactive layer divided into several thin slabs and C-F polymer layer dependent on the H/N ratio, and use of "smart voxels" [1-2]. We successfully predicted the etching properties such as the etch rate, polymer layer thickness, and selectivity for Si, SiO_2, and SiN films along with process variations and demonstrated the 3D damage distribution time-dependently during SW etching on MOSFETs and FinFETs. We confirmed that a large amount of Si damage was caused in the source/drain region with the passage of time in spite of the existing SiO_2 layer of 15 nm in the over etch step and the Si fin having been directly damaged by a large amount of high energy H during the removal step of the parasitic fin spacer leading to Si fin damage to a depth of 14 to 18 nm. By analyzing the results of these simulations and our previous simulations [3,4], we found that it is important to carefully control the dose of high energy H, incident energy of H, polymer layer thickness, and over-etch time considering the effects of the pattern structure, chamber-wall condition, and wafer open area ratio. In collaboration with Masanaga Fukasawa and Tetsuya Tatsumi, Sony Corporation.

*We thank Mr. T. Shigetoshi and Mr. T. Kinoshita of Sony Corporation for their assistance with the experiments.

[1]N. Kuboi *et al.*, Proc. Symp. Dry Process, 2014, p. 29.
[2]N. Kuboi *et al.*, presented at AVS 61st Int. Symp. & Exhib., 2014, PS-TuM4.
[3]N. Kuboi *et al.*, Jpn. J. Appl. Phys. **49**, 08JD01 (2010).
[4]N. Kuboi *et al.*, J. Vac. Sci. Technol. A **31**, 061304 (2013).

Contributed Papers

11:00

OR2 3 Conceptual Design of Electron-Beam Generated Plasma Tools* ANKUR AGARWAL, SHAHID RAUF, LEONID DORF, KEN COLLINS, *Applied Materials Inc.* DAVID BORIS, SCOTT WALTON, *Plasma Physics Division, Naval Research Laboratory* Realization of the next generation of high-density nanostructured devices is predicated on etching features with atomic layer resolution, no damage and high selectivity. High energy electron beams generate plasmas with unique features that make them attractive for applications requiring monolayer precision. In these plasmas, high energy beam electrons ionize the background gas and the resultant daughter electrons cool to low temperatures via collisions with gas molecules and lack of any accelerating fields. For example, an electron temperature of <0.6 eV with densities comparable to conventional plasma sources can be obtained in molecular gases. The chemistry in such plasmas can significantly differ from RF plasmas as the ions/radicals are produced primarily by beam electrons rather than those in the tail of a low energy distribution. In this work, we will discuss the conceptual design of an electron beam based plasma processing system. Plasma properties will be discussed for Ar, Ar/N_2, and O_2 plasmas using a computational plasma model, and comparisons made to experiments. The fluid plasma model is coupled to a Monte Carlo kinetic model for beam electrons which considers gas phase collisions and the effect of electric and magnetic fields on electron motion. The impact of critical operating parameters such as magnetic field, beam energy, and gas pressure on plasma characteristics in electron-beam plasma processing systems will be discussed.

*Partially supported by the NRL base program.

11:15

OR2 4 Surface rippling by oblique ion incidence during plasma etching of silicon: Experimental demonstration using sheath control plates NOBUYA NAKAZAKI, HARUKA MATSUMOTO, KOJI ERIGUCHI, KOUICHI ONO, *Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University* In the microfabrication of 3D transistors (e.g. Fin-FET), the sidewall roughness, such as LER and LWR caused by off-normal or oblique ion incidence during plasma etching, is a critical issue to be resolved, which in turn requires a better understanding of the effects of ion incidence angle θ_i on surface roughening. This paper presents surface roughening and rippling by oblique ion incidence during inductively coupled plasma etching of Si in Cl_2, using the experimental setup as in our previous study [1]. The oblique ion incidence was achieved by sheath control plates, which were placed on and electrically connected to the wafer stage. The plates had slits to vary the sheath structure thereon and to extract ions from plasma to samples on the bottom and/or side of the slits. The results indicated that at $\theta_i \approx 40°$ or oblique incidence; ripple structures were formed on surfaces perpendicularly to the direction of ion incidence, on the other hand, at $\theta_i \approx 80°$ or grazing incidence, small ripples or slit like grooves were formed on surfaces parallel to the direction of ion incidence, as predicted in our previous numerical investigations [2].

[1]N. Nakazaki *et al.*, J. Appl. Phys. **116**, 223302 (2014).
[2]H. Tsuda *et al.*, J. Vac. Sci. Technol. B **32**, 031212 (2014).

THURSDAY MORNING \ OR2

11:30

OR2 5 Apparatus and Method to Plasma Etch Inner Surface of the Varied Diameter Cylindrical Structure JANARDAN UPADHYAY, DO IM, J. PESHL, S. POPOVIC, *Old Dominion University* ANNE-MARIE VALENTE-FELICIANO, L. PHILLIPS, *Thomas Jefferson National Accelerator Facility* L. VUSKOVIC, *Old Dominion University* Plasma processing of inner surfaces of cylindrical structures imposes a coaxial method of discharge generation. It is exemplified with a superconducting radio-frequency cavity made of Niobium, which is a cylindrical structure with variable diameter. It was etched using the coaxial RF discharge operated at 13.56 MHz in Ar/Cl_2 mixture. The cavity is tested on RF performance before and after the plasma etching and the test results are be presented. In the coaxial approach one is faced with the development of a negative self-bias potential on the inner electrode in coaxial plasma, which makes processing of outer wall difficult. The processing of the cylindrical structure with varied diameter has two unique problems of having the variation in plasma sheath asymmetry and the extreme loading effect due to depletion of radical density along the gas flow direction. To overcome these problems, the shape of inner electrode is optimized for asymmetry reduction and a corrugated structure pattern is chosen. Further, a segmented plasma processing method is chosen that includes relative motion of the gas inlet and inner electrode. The coaxial cylindrical discharge was characterized with the help of optical emission spectroscopy and the correlation between plasma parameters and etching rates is presented and discussed.

11:45

OR2 6 Photoluminescence of GaN Film Exposed to Chlorine-Containing Plasma DAISUKE OGAWA, YOSHITSUGU BANNO, YOSHITAKA NAKANO, KEIJI NAKAMURA, *Chubu University* Gallium nitride (GaN) has been an attractive semiconductor material for the application to not only light emitting diodes, but also high power devices. The advantage of the material is that it can be fabricated to maximize the number density of devices a single wafer. In our current technology, we mainly utilize low-temperature plasma for dry etching. In fact, GaN generally requires chlorine-containing plasma for chemical etching. However, the use of plasma has a drawback that can induce unwanted changes on the fabricating devices in some conditions. This is called as plasma-induced damage (PID). We have so far monitored the development of PIDs with photoluminescence (PL) emitted from the GaN surface during argon plasma process. In this time, we exposed a GaN film to chlorine-containing plasma and monitored the PID development. Our PL measurements show that the chlorine-containing plasma almost gave no change in PL property of GaN, while argon plasma gave drastic changes. This is because the speed of etching by chlorine species was faster than the speed of damage creations by plasma. In this presentation, we will show further results of this experiment along with some analyses for the purpose of industrial application.

SESSION OR3: ATMOSPHERIC DISCHARGES: PULSES AND STREAMERS

Thursday Morning, 15 October 2015; Room: 305 AB at 10:00; Peter Bruggerman, University of Minnesota, presiding

Invited Papers

10:00

OR3 1 2D fluid simulations of discharges at atmospheric pressure in reactive gas mixtures*

ANNE BOURDON, *LPP, Ecole Polytechnique, France*

Since a few years, low-temperature atmospheric pressure discharges have received a considerable interest as they efficiently produce many reactive chemical species at a low energy cost. This potential is of great interest for a wide range of applications as plasma assisted combustion or biomedical applications. Then, in current simulations of atmospheric pressure discharges, there is the need to take into account detailed kinetic schemes. It is interesting to note that in some conditions, the kinetics of the discharge may play a role on the discharge dynamics itself. To illustrate this, we consider the case of the propagation of $He-N_2$ discharges in long capillary tubes, studied for the development of medical devices for endoscopic applications. Simulation results put forward that the discharge dynamics and structure depend on the amount of N_2 in the $He-N_2$ mixture. In particular, as the amount of N_2 admixture increases, the discharge propagation velocity in the tube increases, reaches a maximum for about 0.1% of N_2 and then decreases, in agreement with experiments. For applications as plasma assisted combustion with nanosecond repetitively pulsed discharges, there is the need to handle the very different timescales of the nanosecond discharge with the much longer (micro to millisecond) timescales of combustion processes. This is challenging from a computational point of view. It is also important to better understand the coupling of the plasma induced chemistry and the gas heating. To illustrate this, we present the simulation of the flame ignition in lean mixtures by a nanosecond pulsed discharge between two point electrodes. In particular, among the different discharge regimes of nanosecond repetitively pulsed discharges, a "spark" regime has been put forward in the experiments, with an ultra-fast local heating of the gas. For other discharge regimes, the gas heating is much weaker. We have simulated the nanosecond spark regime and have observed shock waves generated by the discharge, in agreement with experiments. Then, we have studied the production of active species for the different regimes of nanosecond repetitively pulsed discharges. We present the relative importance of gas heating and the production of active species for the ignition of lean H_2-air and CH_4-air mixtures.

*This work has been partially supported by the project ANR DRACO (Grant No. ANR-13-IS09-0004).

10:30

OR3 2 Thomson scattering diagnostics of atmospheric pressure plasmas - Pulsed filament discharges and plasma jets

KENTARO TOMITA,* *Kyushu University*

Recently, non-thermal atmospheric-pressure plasmas have received much attention. Because the characteristics of the plasmas are governed by free electrons, measurements of the electron density (n_e) and electron temperature (T_e) are a prerequisite for understanding plasma behavior. To contribute to the understanding of non-thermal atmospheric-pressure plasmas, we have been developing a laser Thomson scattering (LTS) technique as a diagnostic method for measuring n_e and T_e of two types of plasmas; a pulsed-filament discharge and He flow plasma jet. The pulsed filament discharge has a short current width (a few tens of ns) and a small size. In order to apply LTS to such plasmas, reproducibility of time and space of the plasmas were improved using a high-speed semiconductor switch. Spatiotemporal evolutions of n_e and T_e of a main discharge have been obtained. Now we try to apply LTS at a time of primary streamer. Regarding to the He flow plasma jet, the discharge was generated with He gas flow with N_2/O_2(20%) or N_2 shielding gas. It was confirmed that the n_e at the center of the plasma with N_2/O_2 shielding gas was around 50% higher than that with the N_2 shielding gas.

*In collaboration with Keiichiro Urabe, The University of Tokyo; Naoki Shirai, Tokyo Metropolitan University; Safwat Hassaballa, Al-Azhar University; Nima Bolouki, Munehiro Yoneda, Takahiro Shimizu, Yuta Sato, and Kiichiro Uchino, Kyushu University.

Contributed Papers

11:00

OR3 3 Sub-nanosecond dynamics of atmospheric air discharge under highly inhomogeneous and transient electric field* PIERRE TARDIVEAU, LIONEL MAGNE, STEPHANE PASQUIERS, PASCAL JEANNEY, BLANDINE BOURNONVILLE, *Laboratoire de Physique des Gaz et des Plasmas, CNRS (UMR 8578), Université Paris-Sud, 91405 Orsay Cedex France* The effects of the application of extreme overvoltages (>500%) in air gaps over less than a few nanoseconds bring us to reconsider the classical physics of streamer used to describe air discharges at atmospheric pressure. Non equilibrium discharges created by extremely transient and intense electric fields in standard conditions of pressure and temperature exhibit unusual diffuse and large structure. In point-to-plane electrode configurations, a plasma cloud is observed which properties depend on voltage pulses features (amplitude, rise time, length, and frequency) and electrodes properties (material, shape, and gap length). Our parametric experimental study is based on fast electrical characterization and sub-nanosecond imaging and shows the different stages of propagation of the cloud. This work details the conditions to maximize the cloud size without moving towards a multi-channel streamer regime. Based on the analysis and the Abel transform processing of the emission of excited states of nitrogen from the discharge, a focus is made on the structuration of the plasma cloud while it is propagating. It shows how much, according to the experimental conditions, the external electric field can be screened by the plasma and, inversely, how deep and how long a high electric field can be sustained in the gap, that is challenging for pulsed atmospheric plasmas applications.

*This work benefits from the financial support of the National Agency of Research within the framework of the project ANR-13-BS09-0014.

11:15

OR3 4 Electric field of streamers propagating along dielectric surfaces DIRK TRIENEKENS, SANDER NIJDAM, GERRIT KROESEN, *Eindhoven University of Technology* THOMAS CHRISTEN, *ABB Switzerland Ltd.* UTE EBERT, *CWI* In electric power devices for high voltage, the interface between solid and gaseous insulation is usually the most critical part with respect to electric discharges that may lead to breakdown. For a better understanding of the underlying fundamental physics of these discharges, we investigate the streamer propagation along dielectric surfaces, with focus on the streamer electric fields and surface charges deposited on the dielectric material. In particular, we constructed a setup that enables us to study the electric field of the streamer in situ. A positive high voltage pulse is generated using a push-pull switch and supplied to a needle close to a birefringent BSO (Bismuth Silicon Oxide) crystal, along which the streamers can then propagate. Using a power LED and polarizing optics, we are able to visualize via the Pockels effect the electric field caused by the discharge. With this, we are able to quantitatively study streamer electric fields with good temporal and spatial resolution, and can estimate lifetimes of the deposited charges.

11:30

OR3 5 Experimental investigations of electrodeless streamer inception* ANNA CHVYREVA, *Eindhoven University of Technology* THOMAS CHRISTEN, *ABB Switzerland Ltd., Corporate-Research* A.J.M. PEMEN, *Eindhoven University of Technology* Experimental investigations of surface streamer discharges were performed to analyze the conditions of surface streamer inception and determine the important parameters of discharge propagation over a dielectric. The present work is devoted to electrodeless streamer inception in an arrangement typically used in an industrial high voltage device. The process of discharge propagation was investigated under AC and pulsed voltage supplies. The main focus of the work was to determine the velocities of streamer propagation over a dielectric surrounded by nitrogen or air environment. These propagation velocities were estimated by means of time-resolved imaging and current measurements of discharge processes. Other important characteristics of pre-breakdown discharge behavior (such as electric field required for the inception and the values of ionization rates) were obtained. Results demonstrate the influence of a dielectric surface on a process of discharge development; the differences between streamers propagating along a dielectric surface in nitrogen and air environment are analyzed and characteristic parameters are compared to discharge development in bulk gas.

*The authors acknowledge support by STW project 12119 and ABB-Switzerland Ltd., Corporate Research.

11:45

OR3 6 Dependence of streamer density on electric field strength on positive electrode NAKAMURA KOKI, OKUYAMA TAKAHUMI, DOUYAN WANG, N. TAKAO, AKIYAMA HIDENORI, *Kumamoto University* KUMAMOTO UNIVERSITY COLLABORATION Pulsed streamer discharge plasma, a type of non-thermal plasma, is known as generation method of reactive radicals and ozone and treatment of exhausted gas. From our previous research, the distance between electrodes has been considered a very important parameter for applications using pulsed streamer discharge. However, how the distance between electrodes affects the pulsed discharge hasn't been clarified. In this research, the propagation process of pulsed streamer discharge in a wire-plate electrode was observed using an ICCD camera for 4 electrodes having different distance between electrodes. The distance between electrodes was changeable at 45 mm, 40 mm, 35 mm, and 30 mm. The results show that, when the distance between electrodes was shortened, applied voltage with a pulse duration of 100 ns decreased from 80 to 60.3 kV. Conversely, discharge current increased from 149 to 190 A. Streamer head velocity became faster. On the other hand, Streamer head density at onset time of streamer head propagation didn't change. This is considered due to the electric field strength of streamer head at that time, in result, it was about 14 kV/mm under each distance between electrodes.

SESSION OR4: ELECTRON-IMPACT IONIZATION

Thursday Morning, 15 October 2015; Room: 303 AB at 10:00; Allison Harris, Illinois State University, presiding

Invited Papers

10:00

OR4 1 Progress in (e, 2e) electron momentum spectroscopy: from the static to the time-resolved regime

MASAHIKO TAKAHASHI, *Institute of Multidisciplinary Research for Advanced Materials, Tohoku University*

Electron momentum spectroscopy (EMS) is a kinematically-complete electron-impact ionization experiment performed under the high-energy Bethe ridge conditions, where the collision kinematics can be described by electron Compton scattering that most nearly corresponds to the collision of two free electrons with the residual ion acting as a spectator. The remarkable feature of this technique is its ability to measure momentum distributions of each electron bound in matter or to look at molecular orbitals in momentum space. We have been exploring atomic and molecular science using EMS, such as 3D orbital imaging for a stable gaseous molecule [Takahashi *et al.*, PRL 2005], observation of the giant resonance phenomenon in the 2nd order projectile-target interactions [Takahashi *et al.*, PRL 2007], and determination of spatial orientation of the constituent atomic orbitals in molecular orbitals [Watanabe *et al.*, PRL 2012]. Recently, we have started to direct our efforts also towards expanding frontiers of EMS, through development of time-resolved EMS (TR-EMS) that employs ultrashort laser (120 fs) and electron (1 ps) pulses in a pump-probe scheme [Yamazaki *et al.*, RSI 2013]. In spite of the low data statistics as well as of the limited time-resolution due to velocity mismatch, our experimental results on the deuterated acetone molecule in its second excited singlet state with a lifetime of 13.5 ps [Yamazaki *et al.*, PRL 2015] have represented the first time that EMS measurements of short lived transient species are feasible, opening the door to time-resolved orbital imaging in momentum space. With further technical development, TR-EMS could eventually enable one to take a series of snapshots of molecular orbitals changing rapidly during chemical reaction, thereby making it possible to exploit a new area for studies of ultrafast molecular dynamics as well as the nature of molecular excited states; it is electrons that bind atoms into molecules, and chemical reactions are all about the rearrangement of these electrons or the change in spatial patterns of the corresponding molecular orbitals. In this contribution, some results of our recent studies will be presented, which may examine the current status and future prospects of EMS.

10:30

OR4 2 Accuracy of Theoretical Calculations for Electron-Impact Ionization of atoms and Molecules*

DON MADISON, *Missouri S&T*

In the last two decades, there have been several close-coupling approaches developed which can accurately calculate the triply differential cross sections for electron impact ionization of effective one and two electron atoms. The agreement between experiment and theory is not particularly good for more complicated atoms and molecules. Very recently, a B-spline R-matrix with pseudostates (BSRPS) approach was used to investigate low energy electron impact ionization of neon and very good agreement with experiment was found. The perturbative 3-body distorted wave (3DW) approach which includes the exact final state electron-electron interaction (post collision interaction - PCI) gave comparably good agreement with experiment. For ionization of molecules, there have been numerous studies of high-energy electron impact. These studies are called EMS (Electron Momentum Spectroscopy) and they were very valuable in determining the accuracy of molecular wavefunctions since the measured cross sections were proportional to the momentum space molecular wavefunction. More recently, lower energy collisions have started to be measured and these cross sections are much more difficult for theory since the detailed kinematics of the experiment become important. So far, the only close coupling calculation reported for ionization of molecules is the time-dependent close-coupling calculation (TDCC) which has been developed for ionization of H_2 and it yields relative good agreement with experiment. Again the molecular 3-body distorted wave (M3DW) gave equally good agreement with experiment. For polyatomic molecules, the only theory available is the M3DW. In this talk, I will show the current status of agreement between experiment and theory for low and intermediate energy single ionization of atoms and molecules.

*Work supported by the NSF and XSEDE.

Contributed Papers

11:00

OR4 3 B-spline R-matrix with pseudo-states calculations for electron-impact excitation and ionization of beryllium* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* The B-spline R-matrix with Pseudo-States (BSRMPS) method [1,2] is employed to treat electron collisions with beryllium atoms. Results for elastic scattering, excitation, and ionization were obtained for all transitions between the lowest 19 states of beryllium in the energy range from threshold to 150 eV. The sensitivity of the predictions is checked by comparing results obtained in different approximations with increasing number of coupled states. The dataset generated from the largest model, coupling over 600 physical and pseudo-states, is believed to be accurate to within a few percent for the cross sections of relevance for plasma modelling.

*This work was supported by the US National Science Foundation under Grants PHY-1212450 and PHY-1430245, and the XSEDE allocation PHY-090031.

[1] O. Zatsarinny, Comput. Phys. Commun. **174**, 273 (2006).
[2] O. Zatsarinny and K. Bartschat, J. Phys. B **47**, 061001 (2014).

11:15

OR4 4 Non-perturbative B-spline R-matrix with pseudo-states calculations for electron-impact excitation-ionization of helium to the n = 3 states of He^{+}* KLAUS BARTSCHAT, OLEG ZATSARINNY, *Drake University* We present fully-differential cross sections for electron-impact ionization plus simultaneous excitation of helium obtained from a non-perturbative close-coupling formalism with our B-spline R-matrix approach [1,2]. Using a large number of pseudo-states we obtain excellent agreement with directly measured cross-section ratios [3,4] for ionization leaving the residual He$^+$ ion in either the $1s$ ground state, the $n = 2$ $(2s + 2p)$ excited states, or the $n = 3$ $(3s + 3p + 3d)$ excited states.

*This work was supported by the United States National Science Foundation under Grants PHY-1212450 and PHY-1430245, and the XSEDE allocation PHY-090031.

[1] O. Zatsarinny and K. Bartschat, Phys. Rev. Lett. **107**, 023203 (2011).
[2] O. Zatsarinny and K. Bartschat, J. Phys. B **47**, 061001 (2014).
[3] S. Bellm *et al.*, Phys. Rev. A **75**, 042704 (2007).
[4] S. Bellm *et al.*, Phys. Rev. A **78**, 032710 (2008).

11:30

OR4 5 Experimental and Theoretical Fully differential cross sections for electron impact ionization of furfuryl molecules* ESAM ALI, *Missouri Univ of Sci & Tech* DARRYL JONES, *School of Chemical and Physical Sciences, Flinders University* KATE NIXON, *Universidade Federal de Juiz de Fora, Brazil* CHUAN-GANG NING, *Tsinghua University, Beijing, China* MICHAEL BRUNGER, *School of Chemical and Physical Sciences, Flinders University* ANDREW MURRAY, *The University of Manchester* DON MADISON, *Missouri Univ of Sci & Tech* Experimental and theoretical Fully Differential Cross Sections (FDCS) are presented for 250 eV electron impact ionization of the highest and next highest occupied molecular orbitals (HOMO and NHOMO). Theoretical results are compared with experiment for in plane scattering with projectile scattering angles of 5°, 10°, and 15°. Different theoretical models are examined - the molecular 3 body distorted wave (M3DW), and the distorted wave Born approximation (DWBA), with the effects of the post collision interaction (PCI) treated either exactly or with the Ward-Macek approximations. These approximations show good agreement with experimental data for binary peaks. However, for the recoil peak region, experiment finds a noticeable peak while theory predicts no peak. No recoil peak suggests no (or very weak) nuclear scattering, so we have investigated the importance of nuclear scattering by moving the nuclei closer to the center of mass.

*This work is supported by the US National Science Foundation under Grant No. PHY-1068237 and XSEDE resources provided by the Texas Advanced Computing Center (Grant No. TG-MCA07S029).

11:45

OR4 6 Two-center interference effects in (e, 2e) ionization of H_2 and CO_2 at large momentum transfer* MASAKAZU YAMAZAKI, ISAO NAKAJIMA, HIRONORI SATOH, NOBORU WATANABE, *IMRAM, Tohoku University, Japan* DARRYL JONES, *Flinders University, Australia* MASAHIKO TAKAHASHI, *IMRAM, Tohoku University, Japan* In recent years, there has been considerable interest in understanding quantum mechanical interference effects in molecular ionization. Since this interference appears as a consequence of coherent electron emission from the different molecular centers, it should depend strongly on the nature of the ionized molecular orbital. Such molecular orbital patterns can be investigated by means of binary (e, 2e) spectroscopy, which is a kinematically-complete electron-impact ionization experiment performed under the high-energy Bethe ridge conditions [1]. In this study, two-center interference effects in the (e, 2e) cross sections of H_2 [2] and CO_2 at large momentum transfer are demonstrated with a high-statistics experiment, in order to elucidate the relationship between molecular orbital patterns and the interference structure. It is shown that the two-center interference is highly sensitive to the phase, spatial pattern, symmetry of constituent atomic orbital, and chemical bonding nature of the molecular orbital.

*This work was partially supported by Grant-in-Aids for Scientific Research (S) (No. 20225001) and for Young Scientists (B) (No. 21750005) from the Ministry of Education, Culture, Sports, Science and Technology.

[1] M. Takahashi, Bull. Chem. Soc. Jpn. **82**, 751 (2009).
[2] M. Yamazaki *et al.*, Phys. Rev. A **90**, 052711 (2014).

SESSION PR1: ATMOSPHERIC PLASMAS I

Thursday Afternoon, 15 October 2015; Room: 301 B at 13:30; Hindric de Vries, Dutch Institute for Fundamental Energy Research, presiding

Invited Papers

13:30

PR1 1 Tailoring the electron dynamics and chemical kinetics in radio-frequency driven atmospheric pressure plasmas*

TIMO GANS, *York Plasma Institute, University of York*

Radio-frequency atmospheric pressure plasmas are versatile and efficient sources for reactive species at ambient room temperature. The non-equilibrium chemical kinetics is initiated and determined by the electron dynamics. Due to the strongly collisional environment and associated short electron energy relaxation times the electron dynamics can be tailored using multi-frequency power coupling techniques, enabling separate control of key parameters like electron density and electron mean energy. Details of the chemical kinetics depend on the feedgas composition and desired application. Measurements and predictive simulations of key reactive species are equally challenging due to the strongly collisional environment and their multi-scale nature in space and time. The most promising approach is the exploitation of complementary advantages in direct measurements combined with specifically designed numerical simulations. The employed diagnostic techniques include picosecond laser spectroscopy, synchrotron VUV spectroscopy, IR absorption spectroscopy and nanosecond optical imaging spectroscopy. The presentation will focus on examples of He-O_2-N_2 mixtures for bio-medical applications and He/Ar-CO_2 mixtures for CO_2 conversion into value-added chemicals.

*This work has been supported by the UK EPSRC (EP/K018388/1 & EP/H003797/1).

Contributed Papers

14:00

PR1 2 Nonlocal effects in electron heating in atmospheric pressure capacitively coupled discharges DENIS EREMIN, TORBEN HEMKE, THOMAS MUSSENBROCK, *Ruhr Universität Bochum* The present work discusses different aspects contributing to the excitation (ionization) pattern formation in highly collisional capacitively coupled discharges operated under atmospheric pressure in the Ω mode by using analytical arguments and results of numerical simulations. Whereas it is common to explain an observed excitation pattern by using the corresponding power absorption profile, it is argued that the two are essentially different, the former possessing an exponential dependence on the electric field in contrast to the latter. Therefore, the peaks in the profiles of the excitation rate and the absorbed power can take place at different spatial locations. A novel effect, previously unreported for the high pressure discharges, is observed, where spatial location of the peak in the excitation profile is shifted by a distance approximately equal to the energy relaxation length from the peaks in the absorbed power and the electric field profiles. This intrinsically nonlocal and kinetic (the energy relaxation length being much larger for the high energy compared to the low energy electrons) effect is particularly pronounced when the electric field is strongly nonuniform with the scale comparable to the energy relaxation length.

14:15

PR1 3 Influence of quenching gas injection on the temperature field in pulse-modulated induction thermal plasma for large scale nanopowder synthesis* YASUNORI TANAKA, WEIXUAN GUO, NAOTO KODAMA, KENTARO KITA, YOSHIHIKO UESUGI, TATSUO ISHIJIMA, *Kanazawa University* SHU WATANABE, KEITARO NAKAMURA, *Nisshin Seifun Group Inc.* We have so far developed a unique and original method for a large-scale nanopowder synthesis method using pulse-modulated induction thermal plasmas with time-controlled feedstock feeding (PMITP-TCFF). The PMITP is sustained by the coil current modulated into a rectangular waveform. Such the current modulation produces an extremely high-temperature thermal plasma in on-time, and in off-time relatively low-temperature thermal plasma. In PMITP-TCFF method, feedstock powder is intermittently injected to the PMITP synchronously during only on-time for its efficient and complete evaporation. That evaporated materials are rapidly cooled down to promote nucleation of nanoparticles during off-time. This report deals with a numerical approach on influence of quenching gas injection on the temperature field in the PMITP. The thermofluid model for the PMITP was developed on the assumption of local thermodynamic equilibrium (LTE). This model accounted for the pulse-modulation of the coil current and the quenching gas injection. It was found that the quenching gas injection works to increase the PMITP temperature inside the plasma torch during on-time, and then to decrease it effectively in the reaction chamber.

*This work is partly supported by JSPS KAKENHI Grant No. 26249034.

14:30

PR1 4 Modeling of Thermal Arcs in Molded Case Circuit Breakers in Air DOUG BREDEN, SHANKAR MAHADEVAN, *Esgee Technologies* LAXMINARAYAN RAJA, *University of Texas at Austin* A general-purpose thermal plasma simulation tool (VizArc) was utilized to model a circuit breaker in atmospheric pressure air. The molded case circuit breaker (MCCB) circuit breaker works by separating two metal contacts when the breaking current is exceeded generating an arc. The self-consistent Lorentz force generated by the current pushes the arc into an array of splitter plates which quench the arc and break the circuit. The arc channel is modeled by coupling the electromagnetic equations with flow governing equations to model a multi-species, single-temperature quasi neutral arc plasma. Conjugate heat transfer to the metal splitter plates and vapor ablation into the gas are included in the model. The opening action of the moving contact armature is simulated dynamically in the simulation. The set of all governing equations and their implementation in the model will be discussed, and then the simulations of the MCCB circuit breaker using the model will be presented.

14:45

PR1 5 Preliminary Study on Generating Condition of Laser Sustained Plasma using 1 kW CW Diode Laser KOJI NISHIMOTO, MAMORU KUMITA, MAKOTO MATSUI, *Shizuoka University* In the laser sustained plasma of conventional laser driven plasma wind tunnel, CO_2 laser have been used. However, the efficiency of is about 10%. Recently, the development of diode laser is remarkable and the energy efficiency of it reaches nearly 80% in laboratory stage. Therefore, in our research group, the generation of laser sustained plasma using diode laser is being tried. In this study, the generation threshold of it was numerically calculated. Assuming that focused laser diameter is 200 um, in the condition of the pressure of 0.1-1 MPa, it was deduced that the threshold of laser power is about 500 W.

SESSION PR2: CAPACITIVELY COUPLED PLASMAS II
Thursday Afternoon, 15 October 2015
Room: 308 AB at 13:30
Edmund Schuengel, West Virginia University, presiding

Contributed Papers

13:30

PR2 1 The role of the singlet metastables in capacitively coupled oxygen discharges JON TOMAS GUDMUNDSSON, *University of Iceland* MICHAEL A. LIEBERMAN, *University of California at Berkeley* The roles of the singlet metastable molecules $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g)$ in a capacitively coupled rf driven oxygen discharge at 50 mTorr are explored using the one-dimensional object-oriented PIC/MCC code oopd1. Earlier we have demonstrated that the metastable molecule $O_2(a^1\Delta_g)$ has a significant influence on the discharge properties such as the electronegativity, the effective electron temperature and the electron heating processes [1]. A recent global model study indicates that the density of $O_2(b^1\Sigma_g)$ state can be higher than the density of the $O_2(a^1\Delta_g)$ state [2]. Thus the oxygen discharge model now includes the $O_2(b^1\Sigma_g)$ molecule and related reactions. The singlet metastable states of the oxygen molecule have significant influence on the discharge properties. Electron heating is only observed in the sheath region and the electron energy probability function becomes even more concave or bi-Maxwellian when the $O_2(b^1\Sigma_g)$ state is included in the simulation. The center electronegativity is in the range of 0.67 - 1.9.

[1]J. T. Gudmundsson and M. A. Lieberman, Plasma Sources Sci. Technol. **24**, 035016 (2015).
[2]D. A. Toneli *et al.*, J. Phys. D accepted 2015.

13:45

PR2 2 Experimental observation of multi-layer excitation structure in capacitively coupled SF6 plasmas* YONG-XIN LIU, FEI GAO, YUAN-HONG SONG, XUE-CHUN LI, YOU-NIAN WANG, *Dalian University of Technology* Electron excitation dynamics in capacitively coupled SF6 plasmas driven at 9 MHz ~ 16 MHz are studied by using phase resolved optical emission spectroscopy (PROES) of trace rare gas. Multi-layer excitation structure inside the bulk plasma of capacitive discharges operating in SF6 is experimentally observed for the first time. Experimental results show that with the decrease of the rf power and/or the increase of the pressure, the multi-layer excitation structure becomes noticeable while the gap between two adjacent layers is almost kept constant. By increasing the driving frequency with a constant electrode gap, however, the number of layers increases while the layer gap decreases. The layer structure disappears at the driving frequency larger than 16 MHz. The electrode gap is found to have a negligible effect on the gap between two adjacent excitation layers, nevertheless only the number of excitation layers is increased when enlarging the electrode gap. The multi-layer formation may be due to a large modulation of the F- negative-ion density throughout the bulk plasma, and is more pronounced at intermediate and low frequencies, since F- negative ions do not respond to the time-varying electric field at high frequencies (>16 MHz).

*This work was supported by the National Natural Science Foundation of China (NSFC) (Grant No. 11335004) and (Grant No.11405018), and the International Science & Technology Cooperation Program of China (Grant No. 2012DFG02150).

THURSDAY AFTERNOON \ PR2

14:00

PR2 3 Investigation of Plasma Uniformity in Pulsed 100 MHz Narrow Gap-Capacitively Coupled Argon Plasma* YUN-CHANG JANG, MYUNGSUN CHOI, HYUN-JOON RHO, SUNG-RYUL HUH, SUNG-YOUNG YOON, SANGWON RYU, GON-HO KIM, *Seoul National University* Capacitively coupled plasmas (CCPs) for industrial applications have a narrow gap between two electrodes and a large exhaust region between electrodes and lateral walls. In this study, uniformity of electron density (ne) distribution was investigated in a 300 mm Φ CCP with outer-electrode space 4 times larger than inter-electrode space. The 100 MHz RF power was applied to top electrode at a pulse repetition rate of 5 kHz. Experiments reveals that the non-uniformity of the ne decreases from 0.60 in the active-glow period to 0.39 in after-glow period. In order to account for this phenomenon in the after-glow, the effective diffusion length representing the ratio of plasma generation volume to effective loss area is introduced. When RF power is turned off, the ne of each space starts to decrease with the specific loss rate determined by each leff. The calculated leff of the outer-electrode space is about 3.7 times longer than that in the outer-electrode space. This implies that ne of the outer-electrode space decay more slowly, leading to improve the uniformity. The details on experimental results and analysis will be presented and discussed.

*This research was supported by BK21 Research Division of Seoul National University for Energy Resources, Ministry of Trade, Industry and Energy Republic of Korea and Consortium of Semiconductor Advanced Research.

14:15

PR2 4 Harmonic generation of microwave frequencies in plasmas PREMKUMAR PANNEERCHELVAM, LAXMINARAYAN L. RAJA, *The University of Texas at Austin* The ability of RF plasma discharges to generate harmonics of the source frequency was reported as early as 1950s by Margenau and Hartmann [1]. Experiments by Krenz and Kino [2] measured up to seventh harmonic in a spherical discharge with considerable efficiencies. Since the Ions and heavy species are usually slow in responding to a high-frequency signal it is the dynamics of electrons that determine the overall discharge characteristics. The equation of motion that governs the electron dynamics in a plasma discharge and the relation between the current and electron velocity is non-linear. These two factors lead to creation of harmonics of the input frequency. In this work we study the physics of harmonic generation in a microdischarge using a computational model. The model is based on fluid description of plasma. A discharge which is electrostatically excited by a microwave frequency source is simulated and its response is measured. The model is used to provide insights into the non-linear process in the plasma that leads to the creation of higher order harmonics. Microdischarges and large-size discharges are analyzed for their ability to produce harmonics.

[1]H. Margenau and L. M. Hartman, "Theory of high frequency gas discharges. II - Harmonic components of the distribution function." Phys. Rev. **73**, 309 (1948).
[2]J. H. Krenz and G. S. Kino, "Harmonic Generation and Parametric Oscillations in Plasma," J. Appl. Phys. **36**, 8 (1965).

14:30

PR2 5 Generation of anomalously energetic suprathermal electrons by an electron beam interacting with a nonuniform plasma DMYTRO SYDORENKO, *University of Alberta, Canada* IGOR D. KAGANOVICH, *Princeton University* PETER L. VENTZEK, LEE

CHEN, *Tokyo Electron America* Generation of anomalously energetic suprathermal electrons was observed in simulation of a high-voltage dc discharge with electron emission from the cathode. An electron beam produced by the emission interacts with the nonuniform plasma in the discharge via a two-stream instability. Efficient energy transfer from the beam to the plasma electrons is ensured by the plasma nonuniformity. The electron beam excites plasma waves whose wavelength and phase speed gradually decrease towards anode. The short waves near the anode accelerate plasma bulk electrons to suprathermal energies. The sheath near the anode reflects some of the accelerated electrons back into the plasma. These electrons travel through the plasma, reflect near the cathode, and enter the accelerating area again but with a higher energy than before. Such particles are accelerated to energies much higher than after the first acceleration. This mechanism plays a role in explaining earlier experimental observations of energetic suprathermal electrons in similar discharges.

SESSION PR3: GAS PHASE PLASMA CHEMISTRY
Thursday Afternoon, 15 October 2015
Room: 305 AB at 13:30
J. P. Booth, Ecole Polytechnique, presiding

Contributed Papers

13:30

PR3 1 Ion-molecule reactions with CF_3 radical* THOMAS M. MILLER, NICHOLAS S. SHUMAN, JUSTIN P. WIENS, JORDAN C. SAWYER, OSCAR MARTINEZ JR., SHAUN G. ARD, ALBERT A. VIGGIANO, *Air Force Research Laboratory* The first measurements of reaction rate coefficients and products are reported for reactions of the radical CF_3 with Ar^+, Xe^+, O_2^+, NO^+, CO_2^+, and $C_2F_5^+$, at 300 K. The work was carried out in a fast flow of typically 1.5 Torr helium buffer gas (4% argon) using the variable electron and neutral density attachment mass spectrometry (VENDAMS) technique. CF_3 was produced via dissociative electron attachment to CF_3I, resulting in CF_3 concentrations that were well-quantified because the plasma diffusion rate, the electron concentration, and the rate coefficient for attachment to CF_3I were separately measured in the experiment. The $Ar^+ + CF_3$ reaction was found to proceed at nearly the calculated collisional rate coefficient, yielding 90% CF_2^+ along with CF_3^+. Reaction of CF_3 with $C_2F_5^+$ is slower and yields 75% $C_2F_4^+$ along with CF_3^+. CF_3 undergoes charge transfer reaction with Xe^+, O_2^+, NO^+, and CO_2^+, yielding CF_3^+. Arguments will be made regarding reaction mechanisms, including the role of spin conservation. Comparisons with Ar^+ and O_2^+ reaction with CH_3 will be made.

*Supported by Air Force Office of Scientific Research, AFOSR-2303EP.

13:45

PR3 2 Key insights into the reacting kinetics of atmospheric pressure plasmas using $He+N_2/O_2/CO_2/H_2O$/Air mixtures* TOMOYUKI MURAKAMI, *Seikei University* A zero dimensional kinetic chemistry computational modeling to identify the important collisional mechanisms and the dominant species in atmospheric pressure plasmas has been developed [1]. This modeling provides an enhanced capability to tailor wide variety of reactive intermediates/species in atmospheric pressure plasmas using $He+N_2/O_2/CO_2/H_2O$/Air mixtures. The influence of the gas constituent, the gas temperature and the excitation frequency (kHz-, RF-, Pulsed-working) on the complex reacting chemical kinetics is clarified. This work also focuses on the benchmarking between the predictive outputs of this computer-based simulations and the diverse experimental diagnostics with particular emphasis on reactive oxygen/nitrogen intermediates/species.

*This work was partly supported by KAKENHI Grant Number 24561054.

[1]T. Murakami *et al.*, Plasma Sources Sci. Technol. **22**, 015003 (2013); **22**, 015003 (2013); **23**, 025005 (2014).

14:00

PR3 3 Picosecond-TALIF and VUV absorption measurements of absolute atomic nitrogen densities from an RF atmospheric pressure plasma jet with $He/O_2/N_2$ gas mixtures* ANDREW WEST, KARI NIEMI, SANDRA SCHRÖTER, JEROME BREDIN, TIMO GANS, ERIK WAGENAARS, *York Plasma Institute, Department of Physics, University of York, York, United Kingdom* Reactive Oxygen and Nitrogen species (RONS) from RF atmospheric pressure plasma jets (APPJs) are important in biomedical applications as well as industrial plasma processing such as surface modification. Atomic oxygen has been well studied, whereas, despite its importance in the plasma chemistry, atomic nitrogen has been somewhat neglected due to its difficulty of measurement. We present absolute densities of atomic nitrogen in APPJs operating with $He/O_2/N_2$ gas mixtures in open air, using picosecond Two-photon Absorption Laser Induced Fluorescence (ps-TALIF) and vacuum ultra-violet (VUV) absorption spectroscopy. In order to apply the TALIF technique in complex, $He/O_2/N_2$ mixtures, we needed to directly measure the collisional quenching effects using picosecond pulse widths (32ps). Traditional calculated quenching corrections, used in nanosecond TALIF, are inadequate due to a lack of quenching data for complex mixtures. Absolute values for the densities were found by calibrating against a known density of Krypton. The VUV absorption experiments were conducted on the DESIRS synchrotron beamline using a unique VUV Fourier-transform spectrometer. Atomic nitrogen densities were on the order of 10^{20} m^{-3} with good agreement between TALIF and VUV absorption.

*UK EPSRC grant EP/K018388/1.

14:15

PR3 4 Sensitivity Analysis in Complex Plasma Chemistry Models* MILES TURNER, *Dublin City University* The purpose of a plasma chemistry model is prediction of chemical species densities, including understanding the mechanisms by which such species are formed. These aims are compromised by an uncertain knowledge of the rate constants included in the model, which directly causes uncertainty in the model predictions. We recently showed that this predictive uncertainty can be large—a factor of ten or more in some cases. There is probably no context in which a plasma chemistry model might be used where the existence of uncertainty on this scale could not be a matter of concern. A question that at once follows is: Which rate constants cause such uncertainty? In the present paper we show how this question can be answered by applying a systematic screening procedure—the so-called Morris method—to identify sensitive rate constants. We investigate the topical example of the helium-oxygen chemistry. Beginning with a model with almost four hundred reactions, we show that only about fifty rate constants materially affect the model results, and as few as ten cause most of the uncertainty. This means that the model can be improved, and the uncertainty substantially reduced, by focussing attention on this tractably small set of rate constants.

*Work supported by Science Foundation Ireland under grant08/SRC/I1411, and by COST Action MP1101 "Biomedical Applications of Atmospheric Pressure Plasmas."

14:30

PR3 5 Chemical Production of Vibrationally Excited Carbon Monoxide from Carbon Vapor and Molecular Oxygen Precursors KRAIG FREDERICKSON, BEN MUSCI, J. WILLIAM RICH, IGOR ADAMOVICH, *Ohio State Univ - Columbus* Recent results demonstrating the formation of vibrationally excited carbon monoxide from carbon vapor and molecular oxygen will be presented. Previous reaction dynamics simulations and crossed molecular beam experiments have shown that gas-phase reaction of carbon atoms and molecular oxygen produces vibrationally excited carbon monoxide. The present work examines the product distribution of this reaction in a collision dominated environment, at a pressure of several Torr. Carbon vapor is produced in an AC arc discharge in argon buffer operated at a voltage of approximately 1 kV and current of 10 A, and mixed with molecular oxygen, which may also be excited by an auxiliary RF discharge, in a flowing chemical reactor. Identification of chemical reaction products and inference of their vibrational populations is performed by comparing infrared emission spectra of the flow in the reactor, taken by a Fourier Transform IR spectrometer, with synthetic spectra. Estimates of vibrationally excited carbon monoxide concentration and relative vibrational level populations will be presented.

14:45

PR3 6 Hydrogen and Ethene Plasma Assisted Ignition by NS discharge at Elevated Temperatures ANDREY STARIKOVSKIY, *Princeton University* The kinetics of ignition in lean H_2:O_2:Ar and C_2H_4:O_2:Ar mixtures has been studied experimentally and numerically after a high-voltage nanosecond discharge. The ignition delay time behind a reflected shock wave was measured with and without the discharge. It was shown that the initiation of the discharge with a specific deposited energy of 10 – 30 mJ/cm^3 leads to an order of magnitude decrease in the ignition delay time. Discharge processes and following chain chemical reactions with energy release were simulated. The generation of atoms, radicals and excited and charged particles was numerically simulated using the measured time – resolved discharge current and electric field in the discharge phase. The calculated densities of the active particles were used as input data to simulate plasma-assisted ignition. Good agreement was obtained between the calculated ignition delay times and the experimental data. It follows from the analysis of the calculated results that the main mechanism of the effect of gas discharge on the ignition of hydrocarbons is the electron impact dissociation of O_2 molecules in the discharge phase. Detailed kinetic mechanism for plasma assisted ignition of hydrogen and ethene is elaborated and verified.

SESSION PR4: ELECTRON COLLISIONS

Thursday Afternoon, 15 October 2015; Room: 303 AB at 13:30; Igor Bray, Curtin University, presiding

Invited Papers

13:30

PR4 1 Ion Momentum Imaging of Dissociative Electron Attachment to Small Molecules*

MICHAEL FOGLE, *Auburn Univ*

In recent years, low energy dissociative electron attachment (DEA) interactions have been of interest to varying biological and technological applications. To study the dynamics resulting from DEA, we used an ion-momentum imaging apparatus based on the Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS) technique in which a molecular beam is crossed by a pulsed electron beam. The beam interaction takes place in a 4π pulsed electrostatic spectrometer that collects the anion fragments resulting from DEA. The molecular beam is formed by a supersonic expansion which results in a well-localized and cold target. Using this apparatus we have investigated the DEA dynamics for several small molecules: CO_2 at the 4 eV shape resonance and the 8 eV Feshbach resonance; N_2O at the 2.3 eV shape resonance; HCCH at the 3 eV shape resonance; and CF_4 near the 7 eV resonance. An overview of these experimental ion-momentum results will be compared to ab initio electronic structure and fixed-nuclei scattering calculations to gauge the resulting dynamics driven by DEA. In many cases, conical intersections play a pivotal role in driving the dynamics. Some of these systems exhibit non-axial recoil conditions indicative of a bending dynamics in the transitory negative ion state while others exhibit a direct axial recoil dissociation without any bending.

*This work is supported by the National Science Foundation under Contract NSF-PHYS1404366.

14:00

PR4 2 Electron Scattering by biomass molecular fragments

MARCO LIMA, *UNICAMP*

The replacement of fossil fuels by biofuels from renewable sources may not be a definite answer for greenhouse gas emissions problems, but it is a good step towards a sustainable energy strategy. Few per cent of ethanol is being mixed to gasoline in many countries and in some of them, like Brazil, a very aggressive program has been developed, using, in large scale, flex fuel engines that can run with any mixture of gasoline and ethanol, including 100% ethanol. Important points are how to produce ethanol in a sustainable way and with which technology? Biomass is a good candidate to enhance the first generation (produced from Corn in USA and from sugarcane in Brazil) production towards the so-called second-generation ethanol, since it has cellulose and hemicellulose as source of sugars. In order to liberate these sugars for fermentation, it is important to learn how to separate the main components. Chemical routes (acid treatment) and biological routes (enzymatic hydrolysis) are combined and used for these purposes. Atmospheric plasmas can be useful for attacking the biomass in a controlled manner and low energy electrons may have an important role in the process. Recently, we have been studying the interaction of electrons with lignin subunits (phenol, guaiacol, p-coumaryl alcohol), cellulose components, β-D-glucose and cellobiose (β(1-4) linked glucose dimer) and hemicellulose components [2] (β-D-xylose). We also obtained results for the amylose subunits α-D-glucose and maltose (α(1-4) linked glucose dimer). Altogether, the resonance spectra of lignin, cellulose and hemicellulose components establish a physical–chemical basis for electron-induced biomass pretreatment that could be applied to biofuel production. In order to describe a more realistic system (where molecules are "wet"), we have obtained the shape resonance spectra of phenol-water clusters, as obtained previously from elastic electron scattering calculations. Our results, obtained in a simple model (phenol in the presence of one and two water molecules), indicate that the well-known indirect mechanism for hydrogen elimination in the gas phase is significantly impacted on by microsolvation, due to the competition between vibronic couplings on the solute and solvent molecules. This fact suggested how relevant the solvation effects could be for the electron-driven damage of biomolecules and the biomass delignification. We have also discussed microsolvation signatures in the differential cross sections that could help to identify the solvated complexes and access the composition of gaseous admixtures of these species. In a collaboration project involving Australia (within the Brazilian Science Without Borders program), Portugal, Spain and Brazil, we have focused on obtaining theoretical and experimental electronic excitation cross sections of phenol and furfural for 10-50 eV electron impact energies. Convergence on electronic multichannel coupling stands as the biggest challenge to obtain agreement between theory and experiments. In my presentation, I will discuss the current status of this project.

Contributed Papers

14:30

PR4 3 Coherence parameter measurements for neon and hydrogen ROBERT WRIGHT, LEIGH HARGREAVES, MURTADHA KHAKOO, *Cal State Univ- Fullerton* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* AL STAUFFER, *York University* We present recent coherence parameter measurements for excitation of neon and hydrogen by 50 eV electrons. The measurements were made using a crossed electron/gas beam spectrometer, featuring a hemispherically selected electron energy analyzer for detecting scattered electrons and double-reflection VUV polarization analyzer to register fluorescence photons. Time-coincidence counting methods on the electron and photon signals were employed to determine Stokes Parameters at each scattering angle, with data measured at angles between 20 – 115 degrees. The data are compared with calculated results using the B-Spline R-Matrix (BSR) and Relativistic Distorted Wave (RDW) approaches. Measurements were made of both the linear (P_{lin} and γ) and circular (L_{perp}) parameters for the lowest lying excited states in these two targets. We particularly focus on results in the L_{perp} parameter, which shows unusual behavior in these particular targets, including strong sign changes implying reversal of the angular momentum transfer. In the case of neon, the unusual behavior is well captured by the BSR, but not by other models.

14:45

PR4 4 Orientation Effects in Excitation-Ionization of Helium* A.L. HARRIS, T.P. ESPOSITO, *Illinois State University* We present fully differential cross sections (FDCS) for electron-impact excitation-ionization of helium when the ionized electron is found outside of the scattering plane. When the final state He+ ion is left in a non-spherically symmetric state, such as a p-state, an orientation for the ion can be defined. Using our 4-Body Distorted Wave and First Born Approximation models, we examine FDCS in search of effects due to the orientation of the final state He+ ion.

*This work was supported by NSF Grant PHY-1505217.

SESSION QR1: PLASMA INTERACTION WITH LIQUIDS II
Thursday Afternoon, 15 October 2015; Room: 301 B at 15:30; Koichi Sasaki, Hokkaido University, presiding

Invited Papers

15:30

QR1 1 Understanding Charge Transfer Reactions at the Interface of Plasmas in Contact with Liquids*
DAVID GO, *University of Notre Dame*

Plasmas in and in contact with liquids offer a very rich physical and chemical environment where a multitude of species (electrons, ions, neutrals) and physical phenomena (light, electric fields) intersect. With emerging applications in medicine, environmental remediation, and materials synthesis, it has become paramount to understand the many processes occurring at the interface in order to design and optimize new technologies. Perhaps the most important plasma species is the electron, and it thus reasonable to assume it can play a critical role when plasmas are brought in contact with liquids as well. Over the past several years, our group has focused on deciphering the nature of electron transfer from a plasma to liquid and the subsequent chemistry the electrons induce. Our experimental configuration is the plasma equivalent of an electrochemical or electrolytic cell, where the cathode and anode are submerged in an electrolyte solution and current is carried by reduction reactions at the cathode and oxidation reactions at the anode. When the cathode is replaced by a plasma, the circuit is explicitly completed by the injection of plasma electrons into the solution where they stably solvate before inducing reduction reactions. Recently, we have demonstrated the first direct detection of these stably solvated electrons using a novel total internal reflection absorption spectroscopy experiment, resulting in the first measurement of the optical absorption spectrum for plasma-solvated electrons. Further, we have shown that the lifetime of these electrons can be significantly reduced if suitable solution- and plasma-phase scavengers are used to react quickly with these electrons. These results highlight the complexity of the plasma-liquid interface and how charge-transfer processes often compete with other chemistry that occurs at the plasma-liquid interface, such as the dissolution of plasma species into the liquid.

*This work was supported by the U.S. Army Research Office under Award Number W911NF-14-1-0241.

Contributed Papers

16:00

QR1 2 Hydrated Electrons at the Plasma-Water Interface* DAVID GRAVES, RANGA GOPALAKRISHNAN, EMI KAWAMURA, MICHAEL LIEBERMAN, *University of California at Berkeley* When atmospheric pressure plasma interacts with liquid water surfaces, complex processes involving both charged and neutral species generally occur but the details of the processes are not well understood. One plasma-generated specie of considerable interest that can enter an adjacent liquid water phase is the electron. Hydrated electrons are well known to be important in radiation chemistry as initiating precursors for a variety of other reactive compounds. Recent experimental evidence for hydrated electrons near the atmospheric pressure plasma-water interface was reported by Rumbach *et al.* [1]. We present results from a model of a dc argon plasma coupled to an anodic adjacent water layer that aims to simulate this experiment. The coupled plasma-electrolyte model illustrates the nature of the plasma-water interface and reveals important information regarding the self-consistent electric fields on each side of the interface as well as time- and space-resolved rates of reaction of key reactive species. We suggest that the reducing chemistry that results from electron hydration may be useful therapeutically in countering local excess oxidative stress.

*Supported by the Department of Energy, Office of Fusion Science Plasma Science Center

[1]Rumbach *et al.*, The solvation of electrons by an atmospheric-pressure plasma, Nature Communications, in press, 2015.

Invited Papers

16:15

QR1 3 Plasma Functionalized Nanocarbon Materials and Their Applications
YONGFENG LI, *China University of Petroleum*

The plasma treatment method is important for modifying carbon nanomaterials since it has the advantage of being nonpolluting. It has the possibility of scaling up to produce large quantities necessary for commercial use. The liquid-related plasma is especially advantageous in avoiding use of toxic stabilizers and reducing agents during the nanoparticle formation process. In this work, both gas phase and liquid phase plasmas are used to modify nanocarbon materials including graphene and carbon nanotubes. The synthesis of metal nanoparticles functionalized nanocarbon materials including carbon nanotubes and graphene has been realized by an environmentally-friendly gas-liquid interfacial method. Furthermore, the new catalysts based on hybrid of nanocarbon materials and metal nanoparticles have been proved to be stable and high catalytic performance in organic molecule transformation reactions. In addition, the modification of few-layer graphene grown by chemical vapour deposition via the nitrogen plasma ion irradiation has been performed, and the modified graphene sheets as counter electrodes in bifacial dye-sensitized solar cells exhibit high performance.

Contributed Papers

16:45

QR1 4 Synthesis of magnetic nanoparticles by atmospheric-pressure plasma electrolysis and observation of liquid flow induced by plasma NAOKI SHIRAI, TAKETO YOSHIDA, TAKUYA AOKI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* For the synthesis of magnetic metal NPs (nanoparticles), we used the electrolysis combined with atmospheric-pressure plasma. Plasma irradiated positive ions or electron to the solution surface; it worked as electrode of electrolysis. In the case of using aqueous solutions of FeCl2, magnetic NPs were synthesized at plasma-liquid interface when electron was irradiated to liquid surface. The plasma was generated in a miniature helium gas flow surrounded by a shielding gas flow controlling the gas condition around the plasma. The condition of magnetic NPs synthesis depended on the shielding gas species of plasma. In the case of using Ar or N2 shielding gas, magnetic NPs were synthesized. On the other hand, in the case of using O2 shielding gas or without shielding gas, magnetic NPs were not synthesized. To synthesize NPs without chemicals such as FeCl2 solutions, we use plasma electrolysis with iron electrode which is immersed in liquid. When plasma electrolysis was operated, iron electrode eluted to Fe cation and it becomes magnetic NPs at plasma-liquid interface. By using this method much of Fe3O4 is synthesized. In addition, we investigated liquid flow of plasma electrolysis by using Schlieren visualization. Liquid flow was observed when plasma electrolysis was operated.

17:00

QR1 5 Gas phase microreaction: nanomaterials synthesis via plasma exposure of liquid droplets* PAUL MAGUIRE,

CHARLES MAHONY, COLIN KELSEY, NEIL HAMILTON, SADEGH ASKARI, MANUEL MACIAS-MONTERO, *University of Ulster* DECLAN DIVER, *GLASGOW UNIVERSITY* DAVIDE MARIOTTI, *University of Ulster* Plasma-liquid interactions are complex but offer considerable scope for use in nanomaterials synthesis. The introduction of individual picolitre micro-droplets into a steady-state low temperature plasma at atmospheric pressure, offers opportunities for enhanced scope and control of plasma-liquid chemistry and material properties. The gas-phase micro-reactor is similar in concept to liquid bubble microfluidics currently under intense research but with enhanced opportunities for scale-up. For nanomaterials and quantum dot synthesis, the addition of a liquid phase within the plasma expands considerably the scope for core-shell and alloy formation. The synthesis and encapsulation within a liquid droplet allows continuous delivery of nanoparticles to remote sites for plasma medicine, device fabrication or surface coating. We have synthesized Au nanoparticles in flight using $AuHCl_4$ droplets with plasma flight times <0.1 ms. Also, Ag nanoparticles have been synthesized downstream via the delivery of plasma exposed water droplets onto $AgNO_3$ laden substrates.

*Funding from EPSRC acknowledged (Grants EP/K006088/1 and EP/K006142/1).

17:15

QR1 6 Facile synthesis of cuprous oxide nanoparticles by plasma electrochemistry* QIANG CHEN, *Fujian Provincial Key Laboratory of Plasma and Magnetic Resonance, Institute of Electromagnetics and Acoustics, Xiamen University, Xiamen 361005, Chin* JIANDI LIU, *Fujian Provincial Key Laboratory of Plasma and Magnetic Resonance, Xiamen University, Xiamen 361005, China* GUANGHUI YUE, *Fujian Key Laboratory of Advanced Materials, College of Materials, Xiamen University, Xiamen 361005, China* Cuprous oxide nanoparticles were synthesized by plasma electrochemistry. In the plasma electrochemistry system, plasma was contacted with the solution as one electrode and a Cu plate immersed in the solutions as the counter electrode. NaCl solution was used as the basic electrolyte and glucose was added as a reaction mediator and/or a reducing agent. The plasma created many reducing and oxidizing species which can react with the Cu ions released from the Cu plate in the solution. Cu_2O nanoparticles with an average diameter of about 30 nm were formed under the competition of reducing and oxidizing reactions. The results show that the concentration of added glucose strongly affects the properties of the products. Corresponding to high, medium and low concentrations of glucose, the products were, respectively, nanoparticles of amorphous Cu_2O, polycrystalline Cu_2O, and a mixture of polycrystalline Cu_2O and $Cu_2Cl(OH)_3$.

*This work was partially supported by the National Natural Science Foundation of China (Grant No: 11405144) and the Fundamental Research Funds for the Central Universities (Grant No: 20720150022).

SESSION QR2: PLASMAS FOR NANOTECHNOLOGIES

Thursday Afternoon, 15 October 2015; Room: 308 AB at 15:30; Tomohiro Nozaki, Tokyo Institute of Technology, presiding

Invited Papers

15:30

QR2 1 Diagnostics of Nano-Particle Formation in Process Plasmas

HOLGER KERSTEN, *Institute of Experimental and Applied Physics, University of Kiel, Kiel, Germany*

The main sources of particle generation during plasma surface processing and the formation of nano-composite materials are (i) the formation of large molecules, mesoscopic clusters and particles in the plasma bulk by chemically reactive gases, and (ii) the formation and incorporation of particles at surfaces (target, substrate) by means of plasma-wall interaction. The plasma process promotes the particle formation by excitation, dissociation and reaction of the involved species in the gas phase. The different stages of the particle growth in the gas phase can be observed by various plasma diagnostics as mass spectrometry, laser induced evaporation, photo-detachment, IR absorption, microwave cavity measurements, Mie scattering and self-excited electron resonance spectroscopy (SEERS). Common diagnostics of particle formation also use the observation and analysis of harmonics and other discharge characteristics. Especially the early stages of the particle growth are not well investigated since they are experimentally inaccessible by standard methods as mentioned above. A novel collection method based on neutral drag was tested in order to get a better insight into the early stages of particle growth. The experiments were performed in an asymmetric, capacitively coupled rf-discharge, where multiple growth cycles can be obtained. Making use of the correlation between the particle growth cycles and the bias voltage as well as the phase angle between discharge current and voltage it was possible to monitor each growth process in-situ. This allowed to collect particles at any desired stage of the growth cycle via the neutral drag method. Size distributions of the nanoparticles at the different stages of the growth cycle were determined ex-situ by transmission electron microscopy. The observed correlations of particle size and bias voltage, which can be used for prediction of the particle growth, are qualitatively explained. Furthermore, the change of the electron density in the plasma during the growth cycles has been monitored by microwave interfereomtery and the nano-particle formation and deposition was observed in-situ by XPS and NEXAFS at a synchrotron beamline. In collaboration with E. von Wahl, A. Hinz, T. Strunskus, V. Schneider, and T. Trottenberg, Institute of Experimental and Applied Physics, University of Kiel, Kiel, Germany.

Contributed Papers

16:00

QR2 2 Study on silicon nanocrystals and polymer bulk heterojunction structures MICHIHIRO SUGAYA, YI DING, SHU ZHOU, TOMOHIRO NOZAKI, *Tokyo Institute of Technology* Silicon nanocrystals (SiNCs) and semiconductor-polymer (P3HT) nanostructured thin film is investigated for better understanding of bulk heterojunction structure of hybrid solar cell and improving its photon-to-electron conversion performance. SiNCs are synthesized by VHF plasma CVD using silicon tetrachloride. SiNC thin film transistor (TFT) was fabricated to investigate carrier transport properties of SiNC network. As a result, hydrogen-terminated SiNCs behave as n-type semiconductor materials, and electron mobility of SiNC network is improved dramatically. In contrast, chlorine-terminated SiNCs behave as metallic materials and show poor electron transport property because of surface doping effect: electrons are not flow over the SiNC network due to a large electronegativity of chlorine. Additionally, when the chlorine-terminated SiNCs are blended with P3HT, new peaks appear in FTIR absorption spectrum. The result implies that the thiophene structure, which forms the hole transporting pathway, may be damaged by highly reactive surface chlorine and therefore the hole transport property of Cl:SiNCs/P3HT blended film would be deteriorated dramatically. These results are well correlated with Cl- and H-terminated/P3HT hybrid solar cell performance.

16:15

QR2 3 High Density Formation of Ta Nanodots Induced by Remote Hydrogen Plasma YAPING WANG, DAICHI TAKEUCHI, KATSUNORI MAKIHARA, AKIO OHTA, SEIICHI MIYAZAKI, *Nagoya University* We have demonstrated the formation of high-density Ta nanodots (NDs) on thermally-grown SiO_2 by exposing electron beam evaporated a-Ge/Ta bi-layer stack to remote H_2 plasma without any external heating. After the remote H_2 plasma exposure, the formation of NDs with an areal density of 9.7×10^{11} cm^{-2} and an average height of $\sim$ 2.1 nm was confirmed. The electrical separation among the Ta-NDs was observed from changes in surface potential due to charging to the dots. XPS analyses indicate etching of a-Ge layer by the remote H_2 plasma exposure, which was accompanied with agglomeration of Ta atoms on the SiO_2 surface caused by local heating associated with the recombination of atomic hydrogen on clean Ta-layer surface.

16:30

QR2 4 Effects of Time Parameter in Pulse Plasma CVD on Narrow-Chirality Distributed growth of Single-Walled Carbon Nanotubes* BIN XU, TOSHIAKI KATO, TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University* Single-walled carbon nanotubes (SWNTs) are promising materials in industry application, since they have many brilliant characteristics However, since the electronic and optical properties of SWNTs strongly depend on chirality, the selective synthesis of SWNTs with desired chiralities is one of the major challenges in nanotubes science and applications. In this study, time-controlled pulse plasma CVD has been developed aiming for the mass production of narrow chirality distributed SWNTs. Through the comparison of continuous plasma CVD and pulse plasma CVD, it is found that the amount of SWNTs can be increased in keeping with the initial narrow chirality distribution by repeating pulse plasma CVD. The effects of pulse time parameter, plasma off time, on the chirality distribution of SWNTs are also investigated. The chirality distribution becomes narrow with an increase in the plasma off time up to 60 sec, then it becomes broad with an increase in the off time. These indicate, adjustment of plasma time parameter in pulse plasma CVD can improve the uniformity of chirality distribution, resulting in the mass production of very narrow chirality distributed SWNTs.

*This work was supported by a Grant-in-Aid for JSPS Fellows Grant Number 15J01481.

16:45

QR2 5 Plasma as a tool for growth of 1D and 2D nanomaterials and their conversions UROS CVELBAR, *Jozef Stefan Institute* The growth of 1D and 2D nanostructures in low pressure oxygen plasma is presented with the special stress on metal-oxide nanowires and their deterministic growth mechanisms. Since the resulting nanostructures not always have required properties for applications their modifications are required. Therefore their conversions into different oxides or sulphites/nitrides are required with either molecules, atoms, electrons or photons.

17:00

QR2 6 Controlling silicon/TiN interface by plasma induced functionalization for quantum computing applications* EVGENIYA LOCK, *Materials Science and Technology Division, Naval Research Laboratory* PENG XU, YANIV ROSEN, TIM KOHLER, ARUNA RAMANAYAKA, *Laboratory of Physical Sciences, University of Maryland* JOSEPH PRESIGIACOMO, *National Research Council, Washington DC* MIKE OSOFSKY, *Materials Science and Technology Division, Naval Research Laboratory* MARK KUSHNER, *Electrical Engineering and Computer Science, University of Michigan* KEVIN OSBORN, *Laboratory of Physical Sciences, University of Maryland* Charged tunneling defects at the superconductor-dielectric interfaces are known to be deleterious to quantum bits (qubits) in superconducting quantum computing. These tunneling defects are believed to be charged atoms or groups of atoms which cause qubit decoherence through electric field modes. Here we investigate the interface of TiN/Si, because this material system allows for high-coherence qubits and resonators. The defects on metal-dielectric interfaces are especially important in a nonequilibrium regime when microwave and bias electric fields are applied simultaneoulsy. In this work, we are discussing the effects of plasma produced -O, -N and -F functional groups on the qubits performance. Furthermore, we present a detailed chemical, structural, morphological surface analysis which are correlated with plasma gas phase chemistry.

*M. Osofsky was supported under Naval Research Laboratory Base Program. J. Presigiacomo is thankful for the NRC Research Fellowship.

17:15

QR2 7 Interface modification and material synthesis of organic light-emitting diodes using plasma technology RONGQING LIANG, QIONGRONG OU, CHENG YANG, KONGDUO HE, XILU YANG, SHAOFENG ZHONG, *Fudan University* PLASMA APPLICATION TEAM Organic light-emitting diodes (OLEDs), due to their unique properties of solution processability, compatibility with flexible substrates and with large-scale printing technology, attract huge interest in the field of lighting. The integration of plasma technology into OLEDs provides a new route to improve their performance. Here we demonstrate the modification of indium-tin-oxide (ITO) work function by plasma treatment, synthesis of thermally activated delayed fluorescence (TADF) materials using plasma grafting (polymerisation), and multi-layer solution processing achieved by plasma cross-linking.

SESSION QR3: NEGATIVE ION AND DUST PARTICLE CONTAINING PLASMAS
Thursday Afternoon, 15 October 2015
Room: 305 AB at 15:30
John Goree, University of Iowa, presiding

Contributed Papers

15:30

QR3 1 Negative ion density in magnetically confined low-pressure argon-acetylene plasmas using laser-induced photodetachment JOELLE MARGOT, GEORGES AL MAKDESSI, AHMAD HAMDAN, *University of Montreal* RICHARD CLERGEREAUX, *Laplace, Toulouse* In plasmas generated in reactive gases such as silane and acetylene, dust particles can spontaneously form provided the residence time of the precursors is large enough for allowing volume interactions to dominate over surface interactions. In discharges at intermediate pressure (e.g. 100 mTorr), anions are considered to be the most likely precursors to dust particles formation. In the present work, we examine the negative ion density in very low pressure conditions, namely 1-10 mTorr. For this purpose, we investigate magnetized dusty plasmas produced in argon-acetylene mixtures in which dust particles have been observed. The negative ion density is measured using a laser photodetachment technique. It is is observed to increase with the magnetic field intensity and to slightly decrease with increasing C_2H_2 percentage in argon. In addition, it decreases with increasing gas pressure. The photodetachment cross section deduced from the photodetachment signal as a function of laser energy is found to be significantly higher than the value expected for the C_2H^- ion, which may be explained by the presence in the plasma of negatively charged dust particles.

15:45

QR3 2 Controlled Fluxes of Silicon Nanoparticles By Extraction from a Pulsed RF Plasma* STEVEN GIRSHICK, CARLOS LARRIBA-ANDALUZ, *Dept. of Mechanical Engineering, University of Minnesota, Minneapolis, MN* Deposition of silicon nanoparticles onto substrates may be a means of growing monocrystalline silicon films at low substrate temperature if the nanoparticles' impact energy and size can be controlled to provide melting or amorphization of the nanoparticle without damaging the underlying film. In order to explore conditions that could produce such controlled fluxes of nanoparticles we numerically model a pulsed RF argon-silane plasma, with a positive DC bias applied during the afterglow phase of each pulse so as to extract and accelerate negatively charged silicon particles. Operating parameters studied include pulse on time, pulse off time, DC bias voltage, RF voltage and pressure. This set of parameters is tested to find conditions under which one can achieve a periodic steady state with repeatable pulse-to-pulse conditions that maximize silicon film growth rates while maintaining nanoparticle impact energies in the range 0.5-2.0 eV/atom. We utilize a previously developed 1-D dusty plasma numerical model, modified to consider pulsing and applied substrate bias. This model self-consistently solves for the coupled behavior of plasma, chemistry, and aerosol. Results show that it is possible by this method to produce nanoparticle fluxes that are tailored with respect to their distribution of impact energies and mass deposition rates.

*Partially supported by US Dept. of Energy Office of Fusion Energy Science (DE-SC0001939), US National Science Foundation (CHE-124752), and Minnesota Supercomputing Institute.

16:00

QR3 3 Capacitively Coupled RF Plasmas for the Synthesis of Silicon Nanocrystals: Scaling and Mechanisms* ARAM H. MARKOSYAN, *U. Michigan* ROMAIN LE PICARD, DAVID H. PORTER, STEVEN L. GIRSHICK, *U. Minnesota* MARK J. KUSHNER, *U. Michigan* Silicon nanocrystals (SNCs) are of interest for light emitting electronics, photovoltaics, and biotechnology. SNCs are produced in low pressure capacitively coupled plasmas (CCPs) sustained in SiH_4 containing mixtures. To optimize these applications, it is necessary to control the size distribution of the SNCs. Particles 3-5 nm diameter are typically tailored by flow rates and power, however the fundamental processes responsible for this size control are not well understood. We developed a 2-d computer model for RF powered CCPs to predict the synthesis of SNCs. An aerosol sectional model was incorporated into the Hybrid Plasma Equipment Model. The reactor [1] is a quartz tube a few mm in diameter through which 100 sccm Ar and 15 sccm $He/SiH_4 = 95/5$ at 2 Torr are flowed. The SNC residence time is 1-2 ms in the dense plasma region near the electrodes. We found that the distribution of plasma potential is important in determining the growth and size distribution of the SNCs. The SNCs having long residence times in the plasma, thereby enabling growth, are usually negatively charged. To ultimately allow these SNCs to flow out of the plasma, the distribution of the plasma potential must enable the particles to be entrained in the neutral gas flow without a significant potential barrier. We also found that agglomeration of particles of <1 nm is important in the rate of growth of SNCs.

*Work supported by DOE (DE-SC0001939) and NSF (CHE-124752).

[1] L. Mangolini *et al.*, Nano Lett. 5, 655 (2005).

16:15

QR3 4 Preliminary results of experimental measurements to determine microparticle charge in a complex plasma* ERIC GILLMAN, BILL AMATUCCI, *Naval Research Laboratory* Microparticles in a dusty plasma typically collect many of the more mobile electrons as they charge up and therefore typically attain a net negative potential. The charge on these microparticles is typically estimated by calculating the charge on a spherical capacitor at the floating potential or by making measurements of particles levitating in the plasma sheath. However, secondary processes can alter the charging process and are significantly altered in the plasma sheath. Currently there is no reliable method to measure microparticle surface charge in the bulk region of complex or dusty plasmas. A novel, non-invasive, experimental method of measuring the charging of microparticles in the bulk region of a plasma will be presented. Ions impinging directly upon the microparticle surface and interacting electrostatically with the charged microparticle, known as collisional and electrostatic Coulomb ion drag, respectively, slows particle acceleration due to gravity as the particle falls through a plasma discharge. Since ion and neutral drag are commonly the dominant forces on microparticles in complex plasmas, the reduced acceleration is measured without a plasma to determine the neutral drag. By repeating the measurement with a plasma and subtracting the neutral drag, the ion drag is obtained. The microparticle net charge is then ascertained from the ion drag on isolated grains falling through a plasma discharge.

*This work was supported by the Naval Research Laboratory Base Program.

16:30

QR3 5 An expression for the h_l factor in low-pressure electronegative plasma discharges PASCAL CHABERT, *LPP, CNRS*

Ecole Polytechnique The positive ion flux exiting a low-pressure plasma discharge is a crucial quantity in global (volume-averaged) models. In discharges containing only electrons and positive ions (electropositive discharges), it is common to write this flux $\Gamma_{\rm wall} = h_l n_{i0} u_B$, where n_{i0} is the central positive ion density, u_B is the positive ion fluid speed at the sheath edge (the Bohm speed), and h_l is the positive ion edge-to-centre density ratio. There are well established formulae for h_l in electropositive discharges, but for discharges containing negative ions (electronegative discharges), the analysis is more complicated. The purpose of this paper is to propose a formula for the h_l factor in electronegative discharges valid in a large parameter space of practical interest. We use the numerical solution of fluid equations including Poisson's equation as a guide to derive an analytical expression that can easily be incorporated in global models.

16:45

QR3 6 Nanoparticle heating in atmospheric pressure plasmas* NICOLAAS KRAMER, *University of Minnesota, Mechanical Engineering* ERAY AYDIL, *University of Minnesota, Chemical Engineering and Materials Science* UWE KORTSHAGEN, *University of Minnesota, Mechanical Engineering* The plasma environment offers a number of attractive properties that allow for the generation of nanoparticle materials that are otherwise hard to produce by other means. Among these are the generally high temperatures that nanoparticles can attain within plasmas, enabling the generation of nanocrystals of high melting point materials. In low pressure discharges, these high temperatures are the result of energetic surface reactions that strongly heat the small nanoparticles combined with the relatively slow heat transfer to the neutral gas. At atmospheric pressure, the nanoparticle intrinsic temperature is much more closely coupled to the neutral gas temperature. We study the heating of nanoparticles in atmospheric pressure plasmas based on a Monte Carlo simulation that takes into account the most important plasma-surface reactions as well as the conductive cooling of nanoparticles through the neutral gas. We find that, compared to low pressure plasmas, significantly higher plasma densities and densities of reactive species are required in order to achieve nanoparticle temperatures comparable to those in low pressure plasmas. These findings have important implications for the application of atmospheric pressure plasmas for the synthesis of nanoparticle materials.

*This work was supported by the DOE Plasma Science Center for Predictive Control of Plasma Kinetics.

17:00

QR3 7 Behavior of Negative Hydrogen Ion and its Beam by Bias and Beam Extraction Voltages* HARUHISA NAKANO, KATSUYOSHI TSUMORI, MASASHI KISAKI, KATSUNORI IKEDA, SHAOFEI GENG, KENICHI NAGAOKA, MASAKI OSAKABE, YASUHIKO TAKEIRI, OSAMU KANEKO, *National Institute for Fusion Science* GIANLUIGI SERIANNI, PIERO AGOSTINETTI, EMANUELE SARTORI, MATTEO BROMBIN, *Istituto Gas Ionizzati del CNR* CHRISTIAN WIMMER, *Max-Planck-Institut for Plasmaphysik* Negative hydrogen ion (H-) dynamics from production to beam extraction in H- source for fusion have not been enough understood in cesium-seeded negative-hydrogen-ion sources. This dynamics understanding contributes constructions of higher performance ion sources. The H- is produced on and emitted from plasma grid electrode (PG) which is boundary electrode between source plasma and beam. The H- density in the vicinity of the PG decreased with bias voltage (between PG and arc chamber) by suppression of H- emission and/or yield. The H- density decrement was observed in H- beam extraction phase and penetrated to 30 mm depth from PG. The depth and H- beam current decreased with bias voltage. One of the possibilities which explain it is extracted H- coming from space in the vicinity of the PG. An object made of ceramic was inserted above the PG aperture. The H- beam intensity decreased if the object was set 9 mm from PG. This does not conflict with the possibility.

*This work is supported by NIFS Research Programs NIFS13ULRR008 and NIFS13ULRR702, and JSPS KAKENHI Grant Numbers 25800307 and 25249134.

17:15

QR3 8 Plasma Particle Lofting LUCAS HEIJMANS, SANDER NIJDAM, *Eindhoven University of Technology* In plasma particle lofting, macroscopic particles are picked up from a surface by an electric force. This force originates from a plasma that charges both the surface and any particle on it, leading to an electric force that pushes particles off the surface. This process has been suggested as a novel cleaning technique in modern high-tech applications, because it has intrinsic advantages over more traditional methods. Its development is, however, limited by a lack of knowledge of the underlying physics. Although the lofting has been demonstrated before, there are neither numerical nor experimental quantitative measures of it. Especially determining the charge deposited by a plasma on a particle on a surface proves difficult. We have developed a novel experimental method using a "probe force." This allows us to, for the first time, quantitatively measure the plasma lofting force. By applying this method to different plasma conditions we can identify the important plasma parameters, allowing us to tailor a plasma for specific cleaning applications. Additionally, the quantitative result can help in the development of new models for the electron and ion currents through a plasma sheath.

SESSION QR4: MODELING AND SIMULATION III

Thursday Afternoon, 15 October 2015; Room: 303 AB at 15:30; Igor Kaganovich, Princeton Plasma Physics Laboratory, presiding

Invited Papers

15:30

QR4 1 Multidimensional, fully implicit, exactly conserving electromagnetic particle-in-cell simulations*
LUIS CHACON, *LANL*

We discuss a new, conservative, fully implicit 2D-3V particle-in-cell algorithm for non-radiative, electromagnetic kinetic plasma simulations, based on the Vlasov-Darwin model [1]. Unlike earlier linearly implicit PIC schemes and standard explicit PIC schemes, fully implicit PIC algorithms are unconditionally stable and allow exact discrete energy and charge conservation. This has been demonstrated in 1D electrostatic [2] and electromagnetic [3] contexts. In this study, we build on these recent algorithms to develop an implicit, orbit-averaged, time-space-centered finite difference scheme for the Darwin field and particle orbit equations for multiple species in multiple dimensions [4]. The Vlasov-Darwin model is very attractive for PIC simulations because it avoids radiative noise issues in non-radiative electromagnetic regimes. The algorithm conserves global energy, local charge, and particle canonical-momentum exactly, even with grid packing. The nonlinear iteration is effectively accelerated with a fluid preconditioner, which allows efficient use of large timesteps, $O(\sqrt{\frac{m_i}{m_e}}\frac{c}{v_{eT}})$ larger than the explicit CFL. In this presentation, we will introduce the main algorithmic components of the approach, and demonstrate the accuracy and efficiency properties of the algorithm with various numerical experiments in 1D and 2D.

*Support from the LANL LDRD program and the DOE-SC ASCR office.

[1]Nielson and Lewis, Methods Comput. Phys. **16**, 367 (1976).
[2]Chen, Chacón, and Barnes, J. Comput. Phys. **230**, 7018 (2011).
[3]Chen and Chaçón, Comput. Phys. Commun. **185**, 2391 (2014).
[4]Chen and Chacon, Comput. Phys. Commun., submitted.

Contributed Papers

16:00

QR4 2 Modeling and control of ion energy distribution functions at the electrodes of multi-frequency capacitively coupled plasmas EDMUND SCHÜNGEL, *West Virginia University* ZOLTÁN DONKÓ, IHOR KOROLOV, ARANKA DERZSI, *Wigner Research Centre for Physics, Hungarian Academy of Sciences* JULIAN SCHULZE, *West Virginia University* The energy of ions flowing onto boundary surfaces in technological plasmas is of crucial importance for applications. In particular, the shape of the ion energy distribution function (IEDF) determines the surface processes. This is why capacitive radio-frequency (RF) plasmas are widely used. It has been found that the mean energy and flux of ions can be controlled separately in dual-frequency discharges. However, advanced methods should allow for a control of not only the mean ion energy, but also of the shape of the IEDF. Here, we present such an approach based on voltage waveform tailoring. A RF voltage consisting of up to 5 harmonics is applied to one electrode. The outcome of PIC/MCC simulations is compared to an analytical model, which tracks the motion of ions in the electric field of the RF sheath and takes charge exchange collisions into account. The IEDF width, i.e. the maximum and mean ion energy, is controlled by tuning the applied harmonics' phases according to the Electrical Asymmetry Effect. Based on a fundamental understanding of the ion dynamics, the IEDF can be customized and specific features of the distribution – such as peaks at intermediate energies – can be generated and shifted along the energy axis by adjusting the shape of the driving voltage waveform.

16:15

QR4 3 Two- and three-dimensional particle-in-cell simulations of ExB discharges* JOHAN CARLSSON, IGOR KAGANOVICH, ALEXANDER KHRABROV, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* ANDREI SMOLYAKOV, *University of Saskatchewan* The Large-Scale Plasma (LSP) Particle-In-Cell with Monte-Carlo Collisions (PIC-MCC) code has been used to simulate several crossed-field (ExB) discharges in two and three dimensions. Two-dimensional (2D) simulations of a cold-cathode electric discharge with power-electronics applications and a Penning discharge will be presented. Three-dimensional (3D) simulation results of a cylindrical Hall thruster with scaled plasma parameters will also be shown and compared to experiment [Ellison2012]. To enable the 2D and 3D ExB discharge simulations, several improvements to the LSP code were made, including implementation of a new electrostatic field solver, external-circuit model and models for particle injection and secondary-electron emission. To ensure the correctness of the collision models used (and particularly important for the cold-cathode-discharge simulations), validation and code benchmarking was done with the LSP and EDIPIC codes in 1D for a glow discharge. Results and conclusions will be presented.

*Work funded by AFOSR and ARPA-E.

[1]C. L. Ellison, Y. Raitses and N. J. Fisch, "Cross-field electron transport induced by a rotating spoke in a cylindrical Hall thruster," Phys. Plasmas **19**, 013503 (2012).

16:30

QR4 4 Numerical parameter constraints for accurate PIC-DSMC simulation of breakdown from arc initiation to stable arcs* CHRISTOPHER MOORE, MATTHEW HOPKINS, STAN MOORE, JEREMIAH BOERNER, KEITH CARTWRIGHT, *Sandia Natl Labs* Simulation of breakdown is important for understanding and designing a variety of applications such as mitigating undesirable discharge events. Such simulations need to be accurate through early time arc initiation to late time stable arc behavior. Here we examine constraints on the timestep and mesh size required for arc simulations using the particle-in-cell (PIC) method with direct simulation Monte Carlo (DMSC) collisions. Accurate simulation of electron avalanche across a fixed voltage drop and constant neutral density (reduced field of 1000 Td) was found to require a timestep $\sim$ 1/100 of the mean time between collisions and a mesh size $\sim$ 1/25 the mean free path. These constraints are much smaller than the typical PIC-DSMC requirements for timestep and mesh size. Both constraints are related to the fact that charged particles are accelerated by the external field. Thus gradients in the electron energy distribution function can exist at scales smaller than the mean free path and these must be resolved by the mesh size for accurate collision rates. Additionally, the timestep must be small enough that the particle energy change due to the fields be small in order to capture gradients in the cross sections versus energy.

*Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. DOE's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

16:45

QR4 5 A tunable microplasma gradient-index lens for millimeter waves AYYASWAMY VENKATTRAMAN, *University of California, Merced* Field-induced electron emission from the cathode and its interaction with microdischarges has gained significant attention in the last few years particularly in the context of microscale gas breakdown. Recent advances in nanofabrication have led to the development of novel cathodes that demonstrate impressive field emission properties with turn-on fields as low as 1 V/μm and field enhancement factors as high as 1000 implying that field emission could play an important role in microplasmas as large as 500 μm. This work presents proof of concept of a novel application of field emission assisted (FEA) microplasmas that exploits the relatively high plasma number densities encountered in these devices. We hypothesize that the number density gradients and the resulting gradient in the microplasma relative permittivity/refractive index can be utilized as a tunable diverging lens with on/off ability to defocus waves in the Terahertz regime. Electron number density profiles obtained from one-dimensional particle-in-cell with Monte Carlo collisions (PIC-MCC) simulations for a typical FEA microplasma are used to determine the relative permittivity and conductivity profiles. Frequency domain wave propagation simulations using these profiles show that sub-mm waves can be controlled using the microplasma lens with the degree of defocusing depending on the wavelength. In spite of the non-zero conductivity, it is shown that the medium is not significantly lossy at the frequencies considered.

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17:00

QR4 6 2D Axisymmetric vs 1D: A PIC/DSMC Model of Breakdown in Triggered Vacuum Spark Gaps STAN MOORE, CHRIS MOORE, JEREMIAH BOERNER, *Sandia National Laboratories* Last year at GEC14, we presented results of one-dimensional PIC/DSMC [1,2] simulations of breakdown in triggered vacuum spark gaps. In this talk, we extend the model to two-dimensional axisymmetric and compare the results to the previous 1D case. Specially, we vary the fraction of the cathode that emits electrons and neutrals (holding the total injection rates over the cathode surface constant) and show the effects of the higher dimensionality on the time to breakdown.

[1]C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation* (McGraw-Hill, New York, 2005).
[2]G. A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows* (Oxford University Press, Oxford, UK, 1994).

17:15

QR4 7 Breakdown in Atmospheric Pressure Plasma Jets: Nearby Grounds and Voltage Rise Time* AMANDA LIETZ, MARK J. KUSHNER, *University of Michigan* Atmospheric pressure plasma jets (APPJs) are being investigated to stimulate therapeutic responses in biological systems. These responses are not always consistent. One source of variability may be the design of the APPJs – the number and placement of electrodes, pulse power format – which affects the production of reactive species. In this study, the consequences of design parameters of an APPJ were computationally investigated using *nonPDPSIM*, a 2 d model. The configuration is a cylindrical tube with one or two ring exterior electrodes, with or without a center pin electrode. The APPJ operates in He/O_2 flowing into humid air. We found that the placement of the electrical ground on and around the system is important to the breakdown characteristics of the APPJ, and the electron density and temperature of the resulting plasma. With a single powered ring electrode, the placement of the nearest ground may vary depending on the setup, and this significantly affects the discharge. With two-ring electrodes, the nearest ground plane is well defined, however more distant ground planes can also influence the discharge. With an ionization wave (IW) that propagates out of the tube and into the plume in tens of ns, the rise time of the voltage waveform can be on the same timescale, and so variations in the voltage rise time could produce different IW properties. The effect of ground placement and voltage waveform on IW formation (ns timescales) and production of reactive neutrals (ms timescales) will be discussed.

*Work supported by DOE (DE-SC0001319) and NSF (CHE-1124724).

THURSDAY AFTERNOON \ QR4

SESSION SF1: ATMOSPHERIC PLASMAS II
Friday Morning, 16 October 2015
Room: 301 B at 8:00
Francesco Fracassi, University of Bari, presiding

Contributed Papers

8:00

SF1 1 Generation of self-organized micro-gap discharge using sapphire dielectrics* MD. ANWARUL ISLAM, SHIZUKA TADA, KOSUKE JUMONJI, SEIJI MUKAIGAWA, KOICHI TAKAKI, *Department of Electrical Engineering and Computer Science, Iwate University* Micro-plasma generated dielectric barrier discharge with independently self-organized structure under certain conditions and plasma photonic crystals (PPC) have been obtained by the self-organization of filaments in an atmospheric dielectric barrier discharge, which has attracted significant attention. In the present study, atmospheric pressure micro-gap discharge was generated by using sapphire and glass dielectric. Since the charge accumulated in the dielectric is estimated to an important factor that affects the state of DBD, and also affects the self-organized structure. Discharge duration has an impact on self-organized mode and glow mode discharge, has carefully compared here with analysis. Here we have compared the discharge current and breakdown voltage phenomena between sapphire and glass dielectric. Moreover, electron density and current density for different dielectric materials has compared as it is principal parameters to show plasma density. On the other hand, filament structures got from ICCD camera were also observed and examined to get proper hexagonal structure which can effect self-organization of filaments as well.

*This work was supported by JSPS KAKENHI Grant Numbers 26390094, 24540530.

8:15

SF1 2 Reaction mechanism of hydrogen generation from ammonia by DBD pulsed plasma TOKO KAWAOKA, YU INOUE, SHINJI KAMBARA, *Gifu University* Ammonia has a number of favorable characteristics, the primary one being its high capacity for hydrogen storage, 17.6 percent, based on its molecular structure. The secondary advantage is that ammonia is carbon-free at the end users, although CO_2 emission on production of ammonia is dependent on the source of energy. Therefore, ammonia is the promising chemical species as a hydrogen carrier. The purpose of this study is to clarify the elementary reaction mechanism of hydrogen generation from ammonia by DBD pulsed plasma. Effect of applied voltages, gas flow rates and concentration of ammonia was investigated, and then behavior of hydrogen generation in the DBD reactor was calculated using an elemental chemical reaction model. Analysis of reaction pathways indicated that reaction rate of hydrogen generation by ammonia decomposition in the DBD reactor was 10E9 times faster than the usual thermal decomposition.

8:30

SF1 3 Electron information of single and dual rf driven capacitive discharges at atmospheric pressure SANGHOO PARK, WONHO CHOE, *Korea Advanced Institute of Science and Technology* SE YOUN MOON, *Chonbuk National University* JIAN JUN SHI, *Donghua University* Driving frequency is one of the most important parameters in low temperature plasma operation due to its strong influence on reactivity and applicability of the plasma in processes such as etching or deposition. As is well known, the dual frequency technology was developed to separately control ion energy and flux in low pressure low temperature plasmas, and it has been widely in practice in industry. In comparison to the low pressure plasma, the role of driving frequency, particularly dual frequency, in electron and ion kinetics has not been much addressed in atmospheric pressure plasmas. In this work, the electrical characteristics and electron information of single (13.56 MHz) and dual frequency (4.52 MHz + 13.56 MHz) atmospheric pressure argon capacitive discharges were experimentally studied within the abnormal α-mode regime. The results show that electron density (n_e) linearly increases with input rf power while electron temperature (T_e) is not influenced substantially in the single frequency plasma. In contrast, independent control of n_e and T_e was achieved in the dual frequency plasma. As the low-frequency voltage increases with the constant high-frequency input power, T_e decreases from 2.5 eV to 1.8 eV, whereas n_e increases from 7.7×10^{11} cm^{-3} to 1.4×10^{12} cm^{-3}.

8:45

SF1 4 Power Control Method for Atmospheric-Pressure Plasma Generator with Electrode Array HIROYASU TAKEI, SATOSHI KURIO, SATOSHI MATSUYAMA, KAZUTO YAMAUCHI, YASUHISA SANO, *Osaka Univ* DEPARTMENT OF PRECISION SCIENCE AND TECHNOLOGY, GRADUATE SCHOOL OF ENGINEERING, OSAKA UNIVERSITY TEAM, RESEARCH CENTER FOR ULTRA-PRECISION SCIENCE AND TECHNOLOGY, GRADUATE SCHOOL OF ENGINEERING, OSAKA UN TEAM In semiconductor, oxide material, and optical element processing, the processing time must be precisely controlled in each area, and the throughput needs to be reduced. Therefore, we proposed a numerically controlled sacrificial atmospheric-pressure plasma oxidation process and experimentally produced an atmospheric-pressure plasma generator with an electrode array. In this paper, we experimentally produced an atmospheric-pressure plasma generator with an electrode array and conducted NC plasma oxidation experiments. In the proposed NC sacrificial oxidation process, it is necessary to control the power so as to maintain a constant oxidation rate, because the plasma area changes during processing. Therefore, we demonstrated effective monitoring of the electrode voltage for this purpose. Finally, we successfully formed oxide films with nanometer thickness accuracy. We expect that this finding will contribute to improving the accuracy of various plasma processes in the future.

9:00

SF1 5 Atmospheric Pressure Thermal-Plasma-Jet Oxidation of 4H-SiC RYOSUKE ISHIMARU, HIROAKI HANAFUSA, KEISUKE MARUYAMA, SEIICHIRO HIGASHI, *Graduate School of Advanced Sciences of Matter, Hiroshima University* One of the most serious problem to improve the performance of SiC-MOSFET is existence of a large amount of interface state between the insulating film and SiC substrate. It is considered that these defects occur due to carbon desorption during oxidation process. In order to contribute to find solutions for this issue, further investigation of oxidation of SiC wafer is necessary. We have investigated the method of high temperature and rapid oxidation of SiC wafer using atmospheric-pressure thermal-plasma-jet (TPJ) in an atmospheric ambient. TPJ oxidation can provide rapid heating and cooling, and higher oxidation temperature which are difficult to realize by other equipment. This study demonstrates oxidation of 4H-SiC using proposed TPJ oxidation, and intends to obtain knowledge about oxidation at over 1300 °C. For the sample oxidized at 1480 °C on average, 18.7 nm SiO_2 layer was formed within 30 s, and the interface state density of 2.3×10^{12} cm^{-2}eV^{-1} at 0.2 eV from the conduction band edge was obtained. This value is comparable to that of the sample of dry oxidation at 1200 °C. In addition, TPJ oxidation has a possibility of a reduction of oxidation time and process costs, because its oxidation rate was about four times as large as that of dry oxidation at 1300 °C.

SESSION SF2: CARBON RELATED MATERIALS DEPOSITION

Friday Morning, 16 October 2015
Room: 308 AB at 8:00
Jyh-Ming Ting, National Cheng Kung University, presiding

Contributed Papers

8:00

SF2 1 Effects of Fluorine Termination of Carbon Nanowall Edges on Their Electrical Properties by Ar/NO/F_2 Mixture Gas Treatments HYUNG JUN CHO, SATOMI TAJIMA, KEIGO TAKEDA, HIROKI KONDO, KENJI ISHIKAWA, MAKOTO SEKINE, *Graduate school of engineering, Nagoya University* MINEO HIRAMATSU, *Faculty of Science and Technology, Meijo University* MASARU HORI, *Institute of innovation for future society research and development center of human and mobility society, Nagoya University* Carbon nanowalls (CNWs) are one of graphene materials. They consist of multiple graphene sheets grown vertically on the substrate and form a maze-like wall structures. Therefore, a chemical termination of high-density graphene edges on the top regions is essential to control their unique properties. In this study, irradiation effects of fluorine (F) atoms generated using Ar/NO/F_2 gas mixture on changes in chemical bonding structure, crystallinity, and electrical properties of the CNWs, fabricated by a radical injection-plasma enhanced CVD (RI-PECVD) system, were investigated. In the Raman spectra, decrease in relative intensity of D-band peak was found after the Ar/NO/F_2 treatment, which indicates crystallinity improvement of CNWs. According to XPS, F incorporation into the CNWs and formation of related C-F bonds obviously occurred. As the exposure temperature increased, both the F contents in the CNWs and crystallinity improvements were enhanced. Furthermore, the higher electrical conductivities were obtained after the Ar/NO/F_2 gas treatment at a higher temperature. We demonstrated that the electrical properties could be controlled by the F termination of the graphene edges without degradation of the crystallinity.

8:15

SF2 2 Colorful carbon nanopopcorns formed by plasma CVD of diamond-like carbon from CH4 and co-deposited C60 followed by reaction with water vapor TOSHIHIRO SHIMADA, WEI XIE, TAKUYA MIURA, TAKASHI YANASE, TARO NAGAHAMA, *Faculty of Engineering, Hokkaido University* We report the synthesis of a new carbon material - diamond-like carbon (DLC) film co-deposited with 1% C60 molecules - by plasma CVD. The synthesized films exhibited strong iridescence colors after being exposed to an atmosphere containing water vapor, whereas they were transparent just after the deposition. The refractive index of the iridescent films was as high as 3.6 at 650 nm. An electron microscopy examination revealed that the film expanded by more than twice while forming 10 - 100 nm sized grain-like structures after its exposure to water vapor. The reaction has been examined experimentally and theoretically: FTIR after exposure to D2O reveals that OH are connected with carbon. Raman spectra were only slightly different from transparent DLC without C60. Quantum chemical calculation revealed that the C60 conected with other carbons in DLC networks can react with water to make OH bonds. It is associated with cage-breaking of C60, which will initiate the deformation of DLC network. This work demonstrates a new concept of incorporating reaction centers in carbon solids by plasma CVD to make carbon-based nanostructures.

8:30

SF2 3 Fabrication of Nanoplatform Based on Vertical Nanographene MINEO HIRAMATSU, MASAKAZU TOMATSU, *Meijo University* HIROKI KONDO, MASARU HORI, *Nagoya University* Nanoplatform based on vertical nanographene with large surface area offers great promise for providing a new class of nanostructured electrodes for electrochemical sensing, biosensing and energy conversion applications. Carbon nanowalls (CNWs) are composed of few-layer graphene standing almost vertically on the substrate, forming a self-supported network of maze-like wall structures. Their morphologies depend on source gases, pressure, process temperature as well as the type of plasma used for the growth. In view of practical use of CNWs for device applications such as biosensors in the form of micro-total analysis system, the structure of CNWs should be controlled in the nucleation and growth stages. Furthermore, post processes including etching and surface functionalization should also be established. In this study, CNWs were synthesized by PECVD methods using ICP and CCP with radical injection employing methane/hydrogen system. We investigated systematically the early growth stage of CNWs to control their structures for the fabrication of nanoplatform based on vertical nanographene. We report the current status of the control of CNW structures by nucleation control as well as post treatment, together with examples of electrochemical applications using CNWs.

8:45

SF2 4 Effect of atomic composition on hardness of Si-containing a-C:H films deposited by ultra-high-speed PECVD at over 100 micron/h* HIROYUKI KOUSAKA, YASUYUKI TAKAOKA, NORITSUGU UMEHARA, *Nagoya University* Plasma CVD is often employed for depositing DLC (Diamond-Like Carbon) due to its excellent capability for coating 3-dimensional shapes; however, its coating speed is typically not so high, ~ 1 μm/h due to the use of low-density DC or RF plasmas. We have proposed an ultra-high-speed DLC coating at over 100 μm/h where much higher-density plasma is sustained by microwave propagation along plasma-sheath interface. In this work, Si-containing a-C:H films (one type of DLC) were deposited on steel substrates by different 2 methods: DC plasma and microwave-excited high-density near plasma, or our newly proposed method, where the gas composition of Ar, CH_4, C_2H_2, and TMS, and the duty ratio of microwave and substrate bias were changed at a fixed substrate bias of -500 V. For example, under the same condition except microwave injection, the deposition rate and hardness of the DLC deposited by DC plasma were 2.5 μm/h and 11.8 GPa, respectively; while the deposition rate and hardness of the DLC deposited by microwave-excited high-density near plasma were 156 μm/h and 20.8 GPa, respectively. The atomic composition of the films was evaluated by XPS for C, O, and Si, and RBS-ERDA for H/C ratio.

*Acknowledgement: This work was supported partially by a "Grant for Advanced Industrial Technology Development (No. 11B06004d)" in 2011-2015 from the NEDO of Japan.

9:00

SF2 5 Single-crystal diamond growth with sub-millisecond-pulsed discharge of microwave plasma* HIDEAKI YAMADA,

AKIYOSHI CHAYAHARA, YOSHIAKI MOKUNO, *AIST, Japan* Single-crystal diamond was homoepitaxially grown by pulse modulated microwave plasma chemical vapor deposition, where pulse-on time was varied into the order of sub-millisecond. Measurements of the optical emission spectra indicate remarkable increase of atomic hydrogen, which is an important radical to maintain the crystal quality. Preliminary growth was conducted and relatively higher growth rate than preceding works was obtained.

*This work was partially supported by Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Next-generation power electronics" (funding agency: NEDO).

SESSION SF3: OPTICAL DIAGNOSTICS II
Friday Morning, 16 October 2015; Room: 305 AB at 8:00; David Smith, General Electric, presiding

Invited Papers

8:00
SF3 1 Challenges in collisional-radiative modelling for low-temperature plasmas: EEDF, species density profiles, and collisional cross section data
XIMING ZHU, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, Bochum 44780, Germany*

Collisional-radiative (CR) models in low-temperature plasmas are a widely investigated topic. These models can predict the metastable density, radical density, and the VUV photon flux from resonance states. Also, they can relate the emission line-ratios from excited species to the plasma parameters (e.g. electron density and temperature) when using optical emission spectroscopy. Although the CR models for low-temperature plasmas have been developed for several decades, they still face several challenges: (a) a Maxwellian EEDF is assumed in many models for simplicity but a large error can be introduced under more typical conditions with non-Maxwellian EEDFs; (b) homogenous density profiles for excited species are often used, though bounded plasmas are generally inhomogeneous; (c) the collisional cross section data for these models may have too large uncertainties. In this work, some recent progress in the research of CR models is reviewed, which attempts to overcome these challenges. A CR model with a variable EEDF profile (possibly Maxwellian or non-Maxwellian) has been developed. With this model the OES line-ratio method can obtain EEDFs in good agreement with those by Langmuir probe in low-pressure inductive/capacitive discharges. Further, a self-consistent CR model that additionally includes the radiation transfer equations is built. In this way, the assumption of a homogeneous density profile of excited species is avoided. The model can predict the actual density profile. At last, we discuss the recent works on measurements of collisional cross section using plasmas and lasers. In particular, we propose a novel approach, i.e. the pulsed laser induced photoelectron beam method, which in principle overcomes several limitations in the previous measurements. Based on these efforts, a new generation of CR models with a more accurate description of EEDF, species densities, and collisional process rates is supposed to come out in the future.

Contributed Papers

8:30
SF3 2 Heavy particle temperatures in low pressure N_2 / H_2 discharges determined via OES* STEFAN BRIEFI, *AG Experimentelle Plasmaphysik, Universitaet Augsburg, Germany* DAVID RAUNER, URSEL FANTZ, *Max-Planck-Institut fur Plasmaphysik, Germany / AG Experimentelle Plasmaphysik, Universitaet Augsburg, Germany* A widespread method for obtaining the gas temperature in low pressure discharges is the determination of the rotational population of a molecule via measuring its emission spectra. This can be done either directly if the particular emission lines of the emission band can be resolved or indirectly via simulating an emission band and adjusting the simulation to the measurement if the lines cannot be resolved. The first method is usually applied to the Fulcher transition of hydrogen (d $^3\Pi_u \rightarrow$ a $^3\Sigma_g^+$, located between 590 and 650 nm); a prominent example of the second method is the second positive system of nitrogen (C $^3\Pi_u \rightarrow$ B $^3\Pi_g$, located between 280 and 450 nm). In order to compare the results obtained by these methods, spectroscopic high resolution measurements have been carried out in H_2 / N_2 discharges in a pressure range of a few Pa. The experimental setup is an ICP with a cylindrical discharge vessel (length 40 cm, diameter 10 cm, made out of quartz glass). Besides the determination of rotational and vibrational temperatures of the nitrogen and hydrogen molecule the emission line profile of the Balmer lines is analyzed to obtain the temperature of atomic hydrogen.

*The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for the support wihtin the project BR 4904/1-1.

8:45
SF3 3 Experiments and numerical simulations to estimate the accuracy of probe assisted laser photo-detachment for negative ion density and temperature measurements NISHANT SIRSE, *Dublin City University* NOUREDDINE OUDINI, *Centre de Développement des Technologies Avancées, Algeria* BERT ELLINGBOE, *Dublin City University, Ireland* Pulsed laser photo-detachment is the most commonly used technique to measure negative ion density and temperature in electronegative plasmas. The technique is based on measuring the excess electron current produced by the photo-detachment of negative ions. It is considered that the negative ion density is proportional to a rise in electron current following laser pulse, whereas, the temperature of negative ions is estimated based on the recovery of electron current to its value prior to the photo-detachment. During the photo-detachment process it is assumed that the background plasma remains unchanged. However, an electrostatic potential barrier is formed between the laser column (electropositive column) and the surrounding electronegative plasma in order to prevent the outward flow of electrons from the

electropositive plasma column. The strength of the potential barrier depends on the various parameters such as electronegative ($\alpha = n_-/n_e$), laser wavelength etc. Neglecting potential barrier leads to an erroneous estimation of negative ion density and temperature. In the present work we have investigated the above effects by using computer simulation which is further verified by experiments in an inductively coupled oxygen plasma.

9:00

SF3 4 Electric Field Measurements in AC Double Dielectric Barrier Discharge Overlapped With Ns Pulse Discharge BENJAMIN GOLDBERG, IVAN SHKURENKOV, IGOR ADAMOVICH, WALTER LEMPERT, *The Ohio State University* Time-resolved electric field measurements by picosecond CARS / 4-wave mixing are carried out in a double dielectric barrier discharge in H2 between two plane electrodes covered by quartz plates and separated by a 3 mm gap, at a pressure of 300 Torr. The discharge is sustained by an AC voltage waveform (amplitude 4 kV, frequency 500 Hz), overlapped with nanosecond pulses (peak voltage 9 kV, pulse FWHM 100 ns), generated when the AC voltage is zero and operated at twice the frequency. Time and spatial resolution of electric field measurements are 10 μs and 1 cm, respectively. Absolute calibration of the diagnostics is done using a sub-breakdown AC sine wave. Measurements taken in the AC discharge without ns pulses show that electric field remains nearly constant during the entire AC discharge period. Adding ns pulses to the AC waveform results in large-volume breakdown generated in the entire electrode gap every half-period, with a well reproduced time delay after each pulse. Each of these "regular" AC breakdowns results in significant electric field reduction in the entire discharge volume. Basically, diffuse plasma produced by ns pulses neutralizes surface charge accumulated during the AC discharge and generates nearly uniform volume ionization, which results in subsequent large-volume breakdown when the AC voltage is applied. The results show that combining the AC waveform with ns pulses transforms the AC discharge from a superposition of random, small scale micro-discharges to regular, large volume discharges.

9:15

SF3 5 Two-dimensional Measurement of N_2 Rotational Temperature Distribution in Atmospheric Positive DC Glow Discharge using Spectroscopic Imaging TAKAO MATSUMOTO, RYO SASAMOTO, HIDEAKI ORII, YASUJI IZAWA, KIYOTO NISHIJIMA, *Fukuoka University* An experimental method of determining a two-dimensional image of the N_2 rotational temperature in stationary atmospheric non-thermal plasma by spectroscopic imaging was presented. In the experiment, a steady-state glow corona discharge was generated by applying a positive DC voltage to a rod-plane electrode in synthetic air. Spectral images of a DC glow discharge were taken using a gated ICCD camera with ultra narrow band-pass filters, corresponding to the head and tail of a N_2 second positive system band (0-2). The qualitative N_2 rotational temperature was obtained from the emission intensity ratio between the head and tail of the N_2 second positive system band (0-2). The directions of observation were toward the lateral side and hemisphere sides of the rod electrode. The change in the distribution of rotational temperature in a positive DC glow discharge due to the amplitude of applied voltage was investigated. As a result, it was confirmed the rotational temperature and its distribution in a positive DC glow corona respectively increased and spread diffusely with increasing applied voltage. In particular, a distinctly high temperature region was formed in positive DC glow corona near the tip of the rod electrode just below the sparkover voltage.

SESSION SF4: PLASMA SURFACE INTERACTIONS II

Friday Morning, 16 October 2015
Room: 303 AB at 8:00
Leigh Winfrey, University of Florida, presiding

Contributed Papers

8:00

SF4 1 Plasma interaction with grooved emissive surface* IRINA SCHWEIGERT, *The George Washington University, Washington DC, USA* SAM LANGENDORF, MITCHELL WALKER, *Georgia Institute of Technology, Atlanta, USA* MICHAEL KEIDAR, *The George Washington University, Washington DC, USA* In this work we study the plasma-wall interaction for the case of grooved surface. A plasma sheath is formed over an emissive boron nitride (BN) plate placed in a DC discharge in argon gas with pressure 10^{-4} Torr. In the experiment the chamber has a cylindrical shape. The aluminum walls of the chamber are grounded and have low secondary electron emission (SEE) yield. The discharge plasma is sustained by an electron beam emitted by a hot cathode. The voltage applied to the cathode is -70 V. The sheath structure is measured near the dielectrical emissive BN plate, which is electrically isolated and has enhanced SEE yield. In simulations we solve self-consistently the Boltzmann equations for electrons and ions and Poisson equation for the electrical potential. The boundary conditions refer to a domain imbedded in uniform quasineutral plasma with Maxwellian electrons and ions. The electron and ion fluxes from outside are constant and have given velocity distributions. Monoenergetic electron beam enters the calculation domain from the boundary. Both in the experiment and calculation we observe enhanced negative charge accumulation over the grooved surface.

*The authors gratefully acknowledge FA9550-11-1-0160.

8:15

SF4 2 Excitation of Ion Acoustic Waves in Plasmas with Electron Emission from Walls A.V. KHRABROV, I.D. KAGANOVICH, Y. RAITSES, *PPPL* D. SYDORENKO, *University of Alberta, Canada* A. SMOLYAKOV, *University of Saskatchewan, Canada* Various plasma propulsion devices exhibit strong electron emission from the walls either as a result of secondary processes or due to thermionic emission. To understand details of electron kinetics in plasmas with strong emission, we have performed kinetic simulations of such plasmas using EDIPIC code. We show that excitation of ion acoustic waves is ubiquitous phenomena in many different plasma configurations with strong electron emission from walls. Ion acoustic waves were observed to be generated near sheath if the secondary electron emission from the walls is strong. Ion acoustic waves were also observed to be generated in the plasma bulk due to presence of an intense electron beam propagating from the cathode. This intense electron beam can excite strong plasma waves, which in turn drive the ion acoustic waves.

8:30

SF4 3 Computational model of electrode erosion in high-pressure moving arcs* VLADIMIR KOLOBOV, ROBERT ARSLANBEKOV, *CFDRC* VALERIAN NEMCHINSKY, *Keizer University* ALEXANDER RABINOVICH, ALEXANDER FRIDMAN, *Drexel University* We will present an overview of our efforts to develop computational model of electrode erosion for ultra-high pressure (10-100 atm), high current density ($\sim 10^9$ A/m^2) magnetically rotated arcs, which are used for gas heating at hypersonic testing facilities. The arc roots move along internal surfaces of copper electrodes in the form of hollow cylinders. The electrode erosion process at high pressures has many common features with the cold electrode erosion of the vacuum arcs with account for the gas-dynamic effects on the electrode-vapor plasma jets generated due to Maecker effect. We will show results of simulations of the arc column rotation induced by the Lorentz force and by the swirling gas flows using adaptive mesh refinement (AMR) technique. Photographs of the arc root traces indicate micro-crater formation of the cathode surface at atmospheric pressure. We will discuss the applicability of the explosive electron emission model and the *ecton (explosion center)* theory to describe electrode erosion of high-pressure arcs.

*Supported by AFOSR STTR Phase II project monitored by Dr. M.Kendra.

8:45

SF4 4 Reaction pathway and mechanism for Gly-Gly and Ala-Ala under pulsed arc discharge on argon-water interface RYOTA MIYANOMAE, YUKA SAKAI, YUSUKE HIRANO, ARMANDO QUITAIN, *Graduate School of Science and Technology, Kumamoto Universit* MITSURU SASAKI, *Graduate School of Science and Technology and Institute of Pulsed Power Science, Kumamoto Universit* KUNIO K, *Hiroshima Shudo University,Hirosima* TETSUO HONMA, *Hachinohe National College, Aomori* GRADUATE SCHOOL OF SCIENCE AND TECHNOLOGY, KUMAMOTO UNIVERSIT TEAM, GRADUATE SCHOOL OF SCIENCE AND TECHNOLOGY AND INSTITUTE OF PULSED POWER SCIENCE, KUMAMOTO UNIVERSIT TEAM, HIROSHIMA SHUDO UNIVERSITY,HIROSIMA TEAM, HACHINOHE NATIONAL COLLEGE, AOMORI TEAM Peptides are molecules having amino acid polymer structure, and are being used as health supplements, pharmaceutical products and sweeteners. In general, they are synthesized by using a condensing agent and enzymes. However, this conventional method has some drawbacks such as the need for a long reaction time and formation of large amounts of byproducts and wastes. To resolve this problem, this study aims to synthesize peptides by pulse discharge plasma under catalyst-free condition. Results showed that using alanylalanine (Ala-Ala) and glycylglycine (Ala-Gly) as raw materials, elongation reaction proceeded by the pulsed discharge at argon-water interface. Formation of oligomers was observed, while decomposition and addition products were also present. The reaction pathway was also elucidated from the obtained products.

9:00

SF4 5 Surface Cross-linking Phenomena of Organic Films Treated by Argon Plasma KONGDUO HE, QIONGRONG OU, *Fudan University* Solution processed multilayer polymer light-emitting diodes (PLEDs) present challenges, especially regarding dissolution of the first layer during deposition of a second layer. We found a plasma approach to form cross-linked surfaces on organic films, which resist the corrosion of organic solvent, confirmed by the profilometer and fluorescence images. The cross-linking phenomenon is much related to the intrinsic chemical structure of the material. Plasma cross-linking technology may open up a new pathway towards fabrication of all-solution processed multilayer PLEDs.

9:15

SF4 6 Rapid Production of Poly-N-Isopropylacrylamide with Nanopulsed Arc Discharge on Water-Argon Interface YUSUKE HIRANO, *Graduate School of Science and Technology, Kumamoto University* MITSURE SASAKI, *Institute of Pulsed Power Science, Kumamoto University* SATOKO OKUBAYASHI, *Department of Advanced Fibro-Science, Kyoto Institute of Tehnology* GRADUATE SCHOOL OF SCIENCE AND TECHNOLOGY, KUMAMOTO UNIVERSITY TEAM, INSTITUTE OF PULSED POWER SCIENCE, KUMAMOTO UNIVERSITY TEAM, DEPARTMENT OF ADVANCED FIBRO-SCIENCE, KYOTO INSTITUTE OF TEHNOLOGY TEAM Poly-(*N*-Isopropylacrylamide) is well known about an exhibition of coil-to-globule transition below the lower critical solution temperature (32°C) in aqueous media [1]. Because of this temperature near the human body, it has focused on as one of functional polymers available to industries [2]. However, the synthesis of PNIPAM has been conventionally conducted in combined harmful solvents for considerable long operating times. In this study, as a candidate technique for polymer productions, we challenged the use of pulsed discharge to the gas-liquid interface in order to generate reactive species such as radicals from water, initiator and argon gas, which can promote the radical polymerization of NIPAM and its production intermediates. We also discuss possible reaction mechanism based on the experimental results.

[1]M. Heskins, J. E. Guillet, J. Macromol. Sci. Chem. **1968**, 1441 .
[2]J. C. Cuggino, C. B. Contreras, A. Jimenez-Kairuz, B. A. Malettp, and C. I. Alvarez Igarzabal, American Chemical Sciety **2014**, 2239.

SESSION TF1: PLASMA INTERACTION WITH LIQUIDS III
Friday Morning, 16 October 2015
Room: 301 B at 10:00
David Go, University of Notre Dame, presiding

Contributed Papers

10:00

TF1 1 Measurement of OH Radical in an Atmospheric Plasma Generated on Water Surface BRANDON BYRNS, ALEX LINDSAY, KRIS FORD, STEVE SHANNO, DETLEF KNAPPE, *NC Sate University* Hyrdoxyl radicals are a well-known oxidizing agent that has many uses in the removal of contaminants from materials in both liquid and gas phases. To this end, an atmospheric plasma, operated at 162 MHz, is used for the production of dissociated reactive species through plasma enhanced vaporization, ionization and the functionalization of liquid precursors via non-thermal plasma treatment. A coaxial source is used that has all components DC grounded allowing for the flow of water through the device creating a layer of water on the surface of the powered electrode. The plasma can be completely sustained through the evaporation of water from the electrode without the need for noble gases or any other feedgas. Air can also be flown through the device with little effect on OH densities but can be used to change the shape of the discharge at the exit of the device, which could be desirable for different applications. The emission spectrum of the discharge is completely dominated by the emissions of the hydroxyl radical. Spatially resolved absorption spectroscopy is performed using a broadband white light source that only requires a single pass through the plasma. OH concentrations have been calculated to be 10^{14}-10^{16} cm^{-3}.

10:15

TF1 2 Gas flow rate dependence of the production of reactive oxygen species in liquid by a plasma-jet irradiation* GIICHIRO UCHIDA, ATSUSHI NAKAJIMA, *Osaka University* TOSHIYUKI KAWASAKI, *Nippon Bunri University* KAZUNORI KOGA, *Kyushu University* KOSUKE TAKENAKA, *Osaka University* MASAHARU SHIRATANI, *Kyushu University* YUICHI SETSUHARA, *Osaka University* Atmospheric nonequilibrium plasma jets have been widely employed in biomedical applications. For biomedical applications, it is an important issue to understand the complicated mechanism of interaction of the plasma jet with liquid. The main purpose of this study is to clarify the effects of the gas flow rate on the production of reactive oxygen species (ROS) in liquid by the plasma-jet irradiation. For this purpose, we performed plasma-jet experiments using the detection medium for oxidation reaction with KI and starch under the various gas flow rates [1]. In the KI-starch solution system, the absorbance of KI-starch solution near 600 nm behaves linear to the total amount of the ROS, and we could relatively estimate the total amount of the ROS from the solution absorbance. The 569-nm absorbance of the KI-starch solution after the irradiation of a plasma jets for 60 s increases from 0.41 to 0.52 when the He gas flow rate is increased from 3 to 9 slm. Our experiment demonstrates that the gas flow rate strongly affects the total amount of the ROS in liquid in the plasma-jet system.

*This study was supported by a Grant-in-Aid for Scientific Research on Innovative Areas "Plasma Medical Innovation" (24108003) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

[1]T. Kawasaki *et al.*, IEEE Trans. Plasma Sci. **41**, 2482 (2014).

10:30

TF1 3 Generation Mechanisms of Hydroxyl Radical and Hydrogen Peroxide in Plasma Generated over Solution NOZOMI TAKEUCHI, NAOTO ISHIBASHI, DAICHI SHIRAKI, *Tokyo Institute of Technology* Plasmas in contact with liquid have been used in many applications such as water treatment using OH radical, generation of hydrogen peroxide, and so on. The understanding of the generation mechanisms of OH radical and hydrogen peroxide is necessary to improve the time and energy efficiencies in these applications. In this study, plasma generated over a solution was used to investigate the mechanisms. A needle electrode was placed 1 mm above a solution and DC or pulsed voltage was applied to the needle whereas the bottom of the solution was grounded. The concentrations of OH radical and hydrogen peroxide were measured while changing experimental conditions. It was revealed that one of the key mechanisms is OH radical generation in gas phase by dissociation of water molecule in the vicinity of the solution, and the other is OH radical generation in liquid phase followed by irradiation of positive ions to the solution.

10:45

TF1 4 In-water plasma generation and its performance using a coaxial DBD device and compact power supply SHIN-ICHI IMAI, Y. SAKAGUCHI, Y. MIYAMOTO, A. ODAGWA, *Panasonic* TATSURU SHIRAFUJI, *Osaka City University* This paper describes in-water plasma generation and its characteristics using a coaxial tungsten electrode and a compact power supply. In-water plasma is formed in an air stream supplied from outside by an air pump. The power supply circuitry, which is based on LC series resonance, was designed using SPICE simulation. We were able to reduce the volume of the power supply to 1.5 liters. The behavior of the in-water plasma and voltage waveform generated by our device and the power supply were simultaneously observed using a high-speed camera system in conjunction with an oscilloscope. The device performance was estimated using the decoloration of indigo carmine during Plasma ON and OFF. The radicals and species in in-water plasma were measured using an ESR-spin-trap method. It was found that O2- and OH radicals are generated during Plasma ON, and OH radicals remain after Plasma OFF.

11:00

TF1 5 Decomposition of n-Dodecane for Hydrogen Production using Microwave in-Liquid Plasma Method ANDI AMIJOYO MOCHTAR, *Ehime University and Hasanuddin University* SHINFUKU NOMURA, SHINOBU MUKASA, HIROMICHI TOYOTA, KOHJI KAWAMUKAI, *Ehime University* HYDROGEN PRODUCTION TEAM The purpose of this paper is to investigate the decomposing of dodecane in produce hydrogen using in-liquid plasma method. Microwave oven as a medium in generating plasma has modified and connected with the generator. The plasma was improved 1.3 times of hydrogen production when the electrode bubbles were created. The hydrogen ratio of the generated gas was created graphite concentrate that can decrease the decomposition of plasma. The steam reforming in plasma was induced the gas production rate increase 1.4 times. The generated hydrogen efficiency of alkaline water electrolysis was reached at 284% and the conventional of steam reforming at 41%.

11:15

TF1 6 One Step Phenol Production from Toluene Solution Using RF In-Liquid Plasma MUHAMMAD AGUNG, SHINFUKU NOMURA, SHINOBU MUKASA, HIROMICHI TOYOTA, *Graduate School of Science and Engineering, Ehime University, Matsuyama, Ehime 790-8577, Japan* HIDEKAZU GOTO, *Osaka University, 1-1 Yamadaoka, Suita, Osaka 565-0871, Japan* OTSUKA KAZUHIKO, *Graduate School of Science and Engineering, Ehime University, Matsuyama, Ehime 790-8577, Japan* The objective of this research is to investigate the possibility of phenol production with one step process directly from solution of toluene and pure water using plasma in-liquid method. Experiments have been conducted using 27,12 MHz Radio Frequency in-liquid plasma to decompose a solution of 30% toluene. When the plasma was formed in the liquid solution, molecule water substance was decomposed to OH radicals, $H\alpha$, $H\beta$ and O by plasma energy. In phenol production using the proposed method, OH radicals play a major role during the process of direct chemical reaction with toluene. In the sample residue liquid solution, phenols spectral lines are observed by GCMS. Experimental investigations clearly show that phenol can be directly produced from toluene.

11:30

TF1 7 Generation of Discharge Plasma in Gas-Liquid Slug Flow KAKERU MANO, YUI HAYASHI, NORIHARU TAKADA, HIDEKI KANDA, MOTONOBU GOTO, *Naoya University* Discharge plasma in contact with aqueous solution has been attracted attention in the application of wastewater treatment nanoparticles generation and medicine. A lot of methods of electric discharge over aqueous solution surface were researched, but contact area between plasma and aqueous solution was small on these methods. Therefore, some methods generated discharge plasma inside bubbles to enlarge contact area of plasma. However, bubbles were difficult to control because of sheer force and buoyancy in these studies. Namely, the discharge conditions varied temporally. We proposed the discharge method using gas-liquid slug flow in the same direction to control bubbles. Slug flow had the gas phase and liquid phase and these were arranged regularly and flow forward in the same direction. Therefore, this study have potential to generate discharge plasma continuously. In the experiment, the discharge plasma was generated linearly along the inner surface of bubble continuously while flowing the gas-liquid slug. All bubbles between electrodes had plasma emission. Optical emission of feed gas (Ar, He, O_2 and N_2) were observed respectively and emission of OH radical and H_α were also observed. Especially, emissions of OH radical were intense relatively. OH radical has high decomposition ability, thus 4-nitroacetanilide was degraded. The decomposition ratio reached 80% by using Ar or O_2 slug flow. However, by using N_2 slug flow, the decomposition ratio reached only 50%.

11:45
TF1 8 Application of strong pulse electric fields for disinfecting of the water mediums ELCHIN GURBANOV, *Azersu OJSC* ARIF HASHIMOV, *Azerenerji OJSC* Now development on use of strong electric fields for water treatment represents a big urgency. In present article influence of high-voltage pulse fields for disinfecting of drinking water and sewage is considered. In researches the high voltage pulsed generator with exit tension about 100 kV and the different electrode systems are used. They promotes the non-uniform distribution of electromagnetic power lines in interelectrode distance and to development of discharge processes in gases, dissolved in water. Depending on parameters of the discharge gap and electrode system (tension polarity, radius of curvature, the bared area of potential electrode and etc.) we observe the various electro physical processes in interelectrode distance. An impact of high pulse voltage periodically cause inside of gas bubbles in water the high-frequency plasma-chemical processes with photoionization. As a result, an ultra-violet radiation and mechanical compressed waves are appeared and perniciously influencing on microorganisms in water. This process periodically proceeds to their full relaxation. Such method of treatment of liquid mediums is considered much more power effective (less energy-intensive) and environmentally clear in comparison with other appendices.

SESSION TF2: PLASMA ETCHING II

Friday Morning, 16 October 2015; Room: 308 AB at 10:00; Demetre Economou, University of Houston, presiding

Invited Papers

10:00
TF2 1 Cryogenic Etching for Sub-10 nm Patterning for Bit Patterned Media Fabrication
DEIRDRE OLYNICK, *Lawrence Berkeley National Laboratory*

Bit patterned media (BPM) is pushing the limits of lithography and plasma etching. In the next 10 years, sub- 10 nm pitch lithography and pattern transfer are required to reach bit densities approaching 10 TB/in^2. For high throughput manufacturing, nanoimprint lithography will be utilized to pattern the disks. Here, I will discuss low-temperature plasma etching for high-resolution nanoimprint template fabrication using block copolymer lithography and double patterning technologies. The template manufacturing process depends on a multitude of plasma etching steps culminating in quartz etching. Initial dimensions will be determined by the capabilities of block copolymer lithography while the ultimate dimensions will be defined using either double or quadruple patterning. Four to seven plasma etching steps will be required to produce the final template. I will discuss our investigations of cryogenic etching processing for BPM template fabrication. Benefits of cryogenic etching can include enhanced selectivity, better profile control, and novel passivant formation. I will cover applicability of cryoetching in silicon, silicon dioxide, carbon based materials, and chromium.

Contributed Papers

10:30
TF2 2 Atomic Layer Etch to Escape Aspect Ratio Dependent Etching-Profile-Selectivity Trade-offs in Plasma Etch ALOK RANJAN, MINGMEI WANG, SONAM SHERPA, *TEL Technology Center, America, LLC* PETER VENTZEK, *Tokyo Electron America, Inc.* Minimizing each of aspect ratio dependent etching (ARDE), profile, selectivity, uniformity are met by trading off one requirement against another. The problem of trade-offs is especially critical at < 10nm technology. Self-limiting processes like atomic layer etching (ALE) promise a way to escape the trade-offs. Industrial implementation of ALE has not occurred due to speed and precision loss from improper balance of self-limiting passivation and its removal. In recent years strides have been made primarily through temporal and/or spatial pulsing. Moderate success has been reported with some of the trade-offs purported to be managed. Difficulty meeting requirements is due to the inability to control ion energy at low and precise values. We overcome many of the practical implementation issues associated with ALE by precise passivation process control. Very low plasma potential, high radical flux and high bombardment flux are indispensable for achieving ALE. We demonstrate that ALE can achieve zero ARDE and infinite selectivity. Experimental results will highlight that careful consideration of surface processes is required to achieve ALE and not simply "slow etching." Profile control will be shown to rely on careful management of the ion energies and angles. Experimental results are compared with simulation results generated using MCFPM [1] and theoretical scaling models to provide context to the work.

[1]M. Wang and M. J. Kushner, J. Appl. Phys. **107**, 023308 (2010).

10:45
TF2 3 Low Damage Etching with Atomic Layer Precision L. DORF, S. RAUF, G. MONROY, K. RAMASWAMY, K. COLLINS, Y. ZHANG, *Applied Materials* In this presentation, we describe a Low Damage Etch Chamber (LoDEC) for atomic layer etching (ALE) comprising: (1) an electron beam source (1–2 keV) for generating radical-poor, low electron temperature ($T_e\sim 0.3$ eV) plasma, (2) a remote plasma source (RPS) for supplying radicals to the substrate, and (3) a bias generator for creating the voltage drop (0–50 V) between the substrate and the plasma to accelerate ions over etch-threshold energies. In LoDEC, we reproduced the conventional *Si*-etch ALE cycling scheme: in 1st part of the cycle, *Cl* atoms are injected by RPS to passivate the surface for $\Delta t = \tau_p$, and in 2nd part, RPS is turned off and etching is done in e-beam Ar/N_2 plasma at low bias power for $\Delta t = \tau_b$. As τ_b is increased, we observe saturation in the etch depth per cycle, Δ_c, signifying that the entire passivation layer is being removed each cycle, resulting in layer-by-layer etching. In LoDEC, this scheme can be implemented at much lower ion energies, E_i, than in conventional tools, potentially resulting in lower damage to advanced materials. We also obtained the dependence of Δ_c on ion energy and τ_p for a given τ_b. Finally, using LoDEC we developed a novel technique for etching *a-Si* in

Cl below known threshold energy, at $E_i \sim 5-7$ eV (TEM shows etch rates of ~ 3–4 nm/min).

11:00

TF2 4 Layer by layer etching of LaAlSiOx MITSUHIRO OMURA, KAZUHITO FURUMOTO, KAZUHISA MATSUDA, TOSHIYUKI SASAKI, ITSUKO SAKAI, HISATAKA HAYASHI, *Toshiba Corporation* In order to fabricate a gate transistor with high-k oxide materials, removal of high-k oxide films after gate electrode etching is necessary for the formation of ohmic contacts on source and drain regions. It is crucial that the removal process of high-k oxide film by dry etching is highly selective to and low in damage to the Si substrate in order to avoid the degradation of device performances. Sasaki et al. have achieved a high LaAlSiOx-to-Si selectivity of 6.7 using C4F8/Ar/H2 plasma [1]. A sequential layer by layer etching could realize low damage etching, similar to atomic layer etching. Therefore, a sequential LaAlSiOx etching process using a H2 surface modification step followed by a removal step using C4F8/Ar plasma is investigated. The etched amount of LaAlSiOx by the C4F8/Ar plasma step doubles with H2 modification. It is confirmed that when the C4F8/Ar plasma treatment time is sufficient to remove the surface modification layer, a self-limiting reaction is realized. Furthermore, it is confirmed that the etched amount per step can be controlled by control of the ion energy of H2 plasma.

[1]T. Sasaki, K. Matsuda, M. Omura, I. Sakai, and H. Hayashi, Jpn. J. Appl. Phys. **54**, 06GB03 (2015).

11:15

TF2 5 Cryogenic etching of Si with SF_6/O_2: a modeling and experimental study STEFAN TINCK, ERIK C. NEYTS, *University of Antwerp* THOMAS TILLOCHER, REMI DUSSART, *University of Orleans* ANNEMIE BOGAERTS, *University of Antwerp* PLASMANT TEAM, GREMI TEAM Cryogenic etching, although already proposed in 1988, has recently seen an immense increase in popularity in microchip development, due to its very promising ability to reduce plasma induced damage of ultra-small features. Here, we wish to obtain a fundamental understanding of the SF_6/O_2 plasma behavior and its interaction with the surface to improve cryogenic etching. We apply numerical models and experiments to describe the plasma behavior and plasma-surface interactions. SF_6/O_2 low-pressure plasmas are investigated at different wafer temperatures ranging between conventional 293 K and cryogenic 173 K. Cryogenic etch rates are slightly higher due to local cooling of the gas above the wafer, resulting in a slightly higher reactive neutral density. Fundamental surface reactions are also investigated with MD simulations. It is found that the probabilities for chemisorption (i.e., sticking) are insignificantly affected by the wafer temperature. However, surface diffusion and thermal desorption occur much slower at cryogenic conditions and, as a result, it is found that a thick layer of physisorbed species is formed during cryoetching, which is absent at room temperature etching, and which facilitates the formation of an oxygen-based passivation layer.

11:30

TF2 6 Etching of GaAs materials by chlorine neutral beam for quantum nanodisks fabrication CEDRIC THOMAS, AKIO HIGO, TAKERU OKADA, SEIJI SAMUKAWA, *Tohoku University* Quantum dots (QD) fabrication is still challenging, either from bottom-up or top-down approaches. We have combined a Bio-Nano-Process (BNP) and a Neutral Beam Etching (NBE) process to make nanopillars, embedding GaAs quantum nanodisks. Using BNP, a self-assembled monolayer array of nanoparticle is deposited on the GaAs surface to form a nanometer size etching mask array. NBE by chlorine neutrals of GaAs is subsequently performed, enabling low-damage etching of nanodisks. During the fabrication process, insights of NBE mechanisms were investigated. It has been found that NBE was really sensitive to the surface oxide, so the nanopillars fabrication needed a good control of surface oxide and NBE parameters. By studying NBE of GaAs with respect to substrate temperature, it was found that NBE has a low activation energy. In the case of RIE within the same condition, a lower activation energy was estimated. It is assumed that the residual oxide on the surface is the main cause for such behavior. Tuning steps prior etching such as hydrogen radical treatment, have been successful for the fabrication of nanopillars. NBE and RIE have shown same order characteristics, however NBE process enables low-damage nanostructures compared to RIE, which is promising for next generation QD devices.

11:45

TF2 7 Etching of Magnetic Tunneling Junctions Materials using a Reactive Ion Beam KYUNG CHAE YANG, SUNG WOO PARK, MIN HWAN JEON, GEUN YOUNG YEOM, *SungKyunKwan University* The etching of magnetic tunneling junctions (MTJs) was investigated using a reactive ion beam (RIB) system with gases such as Ar, NF_3, CH_3OH and CO/NH_3. Improved etch characteristics were observed with CH_3OH or CO/NH_3 in comparison with Ar or NF_3, possibly due to the enhanced volatile product formation of CH_3OH or CO/NH_3 with MTJ materials by showing lower sidewall residue on the etched features and due to the high etch selectivity over W or TiN. Especially, CO/NH_3 reactive ion beam was the most effective for the MTJ etching by showing the most anisotropic MTJ etch profiles.

12:00

TF2 8 Dry Etching of Si_3N_4, SiO_2 and Si Using Remote Plasma Sources Sustained in NF_3 Mixtures* SHUO HUANG, *U. Michigan* VLADIMIR VOLYNETS, SANGHEON LEE, IN-CHEOL SONG, SIQING LU, *Samsung Electronics Ltd.* JAMES HAMILTON, JONATHAN TENNYSON, *U. College London* MARK J. KUSHNER, *U. Michigan* Remote plasma sources (RPS) are used in microelectronics fabrication to produce fluxes of radicals for etching and passivation in the absence of damage by charging and energetic ions. RPS reactors use distance and grids to reduce or eliminate charged particle fluxes from reaching the wafer. Nitrogen trifluoride (NF_3) is often used in RPS due to the efficiency of producing F atoms by dissociative attachment. RPS sustained in NF_3 gas mixtures, such as $Ar/NF_3/O_2$, increases the variety of reactive species, for example, N_xO_y and FO, and so may enable optimization the etching rates of Si_3N_4, SiO_2 and Si. Meanwhile, by using pulsed power or pulsed gas sources, fluxes of F, O and N_xO_y may be optimized to achieve various etch rates. In this paper, we report on a computational investigation of RPS sustained in different NF_3 containing gas mixtures at pressures of less than a few Torr using continuous and pulsed power for low-damage plasma etching applications. The electron impact cross sections for NF_3, NF_2, and NF were produced using ab initio computational techniques based on the molecular R-matrix method. A reaction mechanism was developed for plasmas sustained in $Ar/NF_3/N_2/O_2$ mixtures and a surface reaction mechanism was developed for etching of Si_3N_4, SiO_2 and Si. Plasma properties and etch rates will be discussed for different pulse-power scenarios and gas mixtures.

*Work supported by Samsung Electronics, SRC and NSF.

SESSION TF3: APPLICATIONS OF PLASMAS

Friday Morning, 16 October 2015; Room: 305 AB at 10:00; Hirotaka Toyoda, Nagoya University, presiding

Invited Papers

10:00

TF3 1 Plasmas and Nanostructures for Energy Applications

SYLVAIN COULOMBE, *Plasma Processing Laboratory, Department of Chemical Engineering, McGill University*

The contribution presents a Plasma Engineer's perspective on the utilization of plasmas and nanostructures produced through plasma processes in the context of energy, keeping in mind potential environmental impacts and process and product sustainability. Already-identified opportunities for plasma source and process development for end-of-pipe treatments are presented, but also for sustainability-inspired processes. In the area of nanomaterial synthesis, how can dry plasma processes making using a simple and environmentally-benign raw materials can be used to replace wet chemistry processes? How can one dictate power supply design for fine-tuned electrical energy utilization and minimal material use? How can plasma sources be used for off-hours electrical-to-chemical energy transformation and chemical energy densification? How can plasma sources be used for resource recovery from urban mines, e-waste and municipal solid waste so as to avoid energy-intensive primary mining, transformation, transportation and disposal of valuable and/or toxic materials? How can plasma-based processes be intensified for waste energy recovery and zero material losses? How can products be fabricated with minimal materials and energy use? How can products that are designed for recycling be fabricated and *de*-fabricated using plasma processes, at minimal energy cost? Some of the emerging works along the above-mentioned lines and conducted by Canadian research institutions are presented.

Contributed Papers

10:30

TF3 2 Carbon nanoparticles in the radiation field of the stationary arc discharge* MIKHAIL SHNEIDER, *Princeton University* The arc discharge between the graphite electrodes burning in the high pressure atmosphere of inert gases is one of the standard methods of nanoparticle synthesis. The arc is a very powerful light emission source, which is close to the blackbody source. We present a simple theoretical model of heating the spherical carbon nanoparticles in the Rayleigh regime of the radiation absorption, depending on their size and the parameters of the radiating arc and the surrounding gas. We consider the conditions specific to the far periphery of the arc, where the degree of ionization is very small and the plasma effects in the heat balance are negligible. The following cooling processes are taken into account: radiative cooling; conductive cooling in collisions with the buffer gas atoms, and thermionic emission. The obtained results show that the nanoparticles temperatures significantly exceed the local temperature of the buffer gas. A quasi equilibrium temperature of the particle is higher the closer this particle is to the arc. The particle temperature is established within 10 microseconds. For this time the convective displacement of the particles is negligible. The heating of nanoparticles by the radiation can affect the process of synthesis. The degree of heating of the particle is determined by the particle's geometry, and this opens additional possibilities for nonintrusive optical diagnostics.

*This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division.

10:45

TF3 3 The structure of carbon needle-shaped materials grown above dehydrated ethanol using DC and AC surface plasma* DMYTRO KOZAK, ETSURO SHIBATA, ATSUSHI IIZUKA, TAKASHI NAKAMURA, *Institute of Multidisciplinary Research for Advanced Materials (IMRAM), Tohoku University, 1, 1 Katahira, 2-Chome, Aobaku, Sendai 980-8577, Japan* The developed method allows growing the carbon needle-shaped materials, which exhibit glassy carbon- and pyrocarbon-like structures, using DC and AC surface plasma on the cathode above dehydrated ethanol.

*This work was supported by the Management Expenses Grants for National Universities Corporations "Nano-Macro Materials, Devices and System Research" from the Ministry of Eduction, Culture, Spots, Science and Technology (MEXT) of Japan.

11:00

TF3 4 Development and investigation of a pulsed screw pinch for the application as a FAIR plasma stripper* MARCUS IBERLER, THILO ACKERMANN, BENJAMIN BRUENNER, FIONA FABER, CHRISTIAN HOCK, JOERG WIECHULA, JOACHIM JACOBY, *Goethe University Frankfurt, Institute for Applied Physics* The purpose of this work is to study a combination of a Z- and a Theta-Pinch Plasma with a dynamic external magnetic field generated by a coil integrated into the discharge circuit. The coil is serially connected with the generated plasma and the pulse forming network. The maximum energy used for the experiment is 5 kJ. The axial and azimuthal fields oscillate with the changing current. So, one goal is to study possible synergy effects between the magnetic fields and the efficiency concerning the magnetic pressure. Furthermore, the density and charge state of the resulting plasma are of interest for possible application as a FAIR Plasma stripper. The pinch plasma is generated by a capacitive hollow cathode discharge. To achieve the interaction between the magnetic fields, a coil is wrapped around the discharge chamber. This way the current, first running through the coil, then as an arc discharge through the chamber, is responsible for both the z- and theta-pinch portions of the screw pinch. The first experiments are made to the left of the Paschen minimum using the breakdown voltage. This work focuses on the optical analysis of the plasma to determine the plasma parameters. A fast shutter camera is used for the spatial resolution of the plasma. In addition time resolved and time integrated spectrographic measurements are made to examine plasma temperature, density and charge state.

*Supported by the BMBF and HIC4FAIR.

11:15

TF3 5 Loop-shaped UV lamp array with uniform irradiation distribution driven by a poly-phase ac discharge/plasma in a multi-pole magnetic field KAZUNORI MATSUMOTO, *Toyama Prefectural University* An ultraviolet (UV) glow lamp in the shape of a loop had been devised by us to improve characteristics of spatial uniformity of irradiating distribution and emitting intensity of brightness. The lamps have been arrayed planarly into a light-emitting box, where spaces among lamps are wholly covered with aluminum thin-mirrors of high reflectivity for UV irradiation and surfaces of four walls surrounding the array are also covered with those. Experimental data measured by using a multi-channel spectroscope showed that spatial irradiation distributions over the emitting box were highly uniform in both longitudinal and horizontal directions, and furthermore in height direction. The results indicate that we are able to perform photo-curing processes homogeneously even if a substrate has a curved surface or the substrate moves relatively, under very small amount of irradiation energy compared with conventional high intensity UV lamps. The presented lamp array is not limited to the photo-curing application and can be used widely in various fields of industry.

11:30

TF3 6 A coherent x-ray source from plasma using high-order harmonic generation* DANE LABAN, SMIJESH ACHARY, NICOLAI KLEMKE, JAMES WOOD, DASHAVIR CHETTY, DAVID KIELPINSKI, IGOR LITVINYUK, ROBERT SANG, *Australian Attosecond Science Facility, Centre for Quantum Dynamics, Griffith University* We present progress towards a tabletop light source of coherent x-rays with energies extending up to 5 keV. High-order harmonic generation (HHG) using an infrared ultrashort pulse in an uncharged gaseous medium is able to produce coherent and directional light with energies extending up to several hundred eV. By using a charged plasma as the HHG medium we will be able to extend the cut-off energy and brightness of the light into the keV region. In our proposed source a plasma containing mostly Cr^{5+} is needed. The difficulties of producing such a light source arise from ensuring the plasma is spatially uniform and of a specific density to allow for efficient phase-matching of the generated light. We will discuss the experimental design, methodology used to obtain the plasma, present results on the characterization of the plasma, and some early results of the HHG spectrum obtained.

*This research is supported by Lockheed Martin and the Australian Research Council.

11:45

TF3 7 Evaluation of iodine as an alternative propellant for gridded electric space propulsion systems* PASCALINE GRONDEIN, TREVOR LAFLEUR, PASCAL CHABERT, ANE AANESLAND, *Laboratoire de Physique des Plasmas - CNRS - UPMC* Most state-of-the-art electric space propulsion systems such as gridded and Hall thrusters use xenon as the propellant gas. However, xenon is very rare, expensive to produce and used in a number of competing industrial applications. Alternatives to xenon are currently being investigated, and iodine has emerged as a potential candidate. Its lower cost, larger availability, its solid state at standard temperature and pressure, its low vapour pressure and its low ionization potential makes it an attractive option. In this work we compare the performances of a gridded ion thruster operating in iodine and in xenon under otherwise similar conditions using a global model. The thruster parameters such as neutral, ion and electron densities and electron temperature were calculated as well as the system performances such as thrust, specific impulse, etc. When running with a neutral gas flow of 1 mg/s, an acceleration potential of 1000 V and RF power of 800 W, the model predicts a thrust of 30 mN for an extraction diameter of 60 mm for both iodine and xenon. The thruster efficiency is however 15% higher for iodine compared to xenon mainly due to the lower ionization energy for iodine and larger ion mass due to the contribution from I2 ions.

*This work has been done within the LABEX Plas@par project, and received financial state aid managed by the Agence Nationale de la Recherche, as part of the programme "Investissements d'avenir."

SESSION TF4: ATMOSPHERIC PRESSURE PLASMA JETS
Friday Morning, 16 October 2015; Room: 303 AB at 10:00; Mikhail Benilov, University of Madeira, presiding

Invited Papers

10:00

TF4 1 Computational Modeling and Simulation of Micron-Scale Discharges and Their Interactions with High-Frequency Electromagnetic Waves

LAXMINARAYAN L. RAJA, *Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin*

In this work we discuss high-fidelity computational modeling of micron-scale discharges and their interactions with electromagnetic waves in the microwave regime. The study is motivated by applications in plasma metamaterials where large arrays of microdischarge structures are used to manipulate incident micro/terahertz waves. We use a combination of classical particle-in-cell (PIC) modeling and fluid modeling approaches to understand breakdown of individual microdischarge structures due to the electromagnetic wave excitation and the operation of stable microdischarges in the presence of these waves, respectively. The effect of length scale, frequency of excitation, surface electron emission physics on breakdown is addressed in detail with the PIC model. The fluid model represents both plasma physics and wave interaction effects. Self-consistent approach for modeling of plasma-wave interaction and the numerical implementation will be discussed in detail. The manipulation of incident electromagnetic waves as a function of individual microdischarge structure is reported. Also, we study non-linear interactions where sufficiently high-intensity electromagnetic waves modify the structure of the individual microdischarges leading. In collaboration with Dmitry Levko and Premkumar Paneerchelvam, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin.

Contributed Papers

10:30

TF4 2 Temporal evolution of the EVDF in a ns-pulsed APPJ in Helium UWE CZARNETZKI, CHRISTIAN SCHREGEL, DIRK LUGGENHÖLSCHER, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum* The temporal evolution of the EVDF in a ns-pulsed jet-discharge operated in Helium is measured by Thomson scattering. Further, spatially and temporally resolved emission spectra and current and voltage waveforms are measured. The discharge consists of two molybdenum electrodes of 20 mm length which form a 1.5 mm high and 0.95 mm wide gap between two glass plates. A 150 ns long voltage pulse of 1-2 kV (5 kHz) is applied. A Nd:YAG laser provides an 8 ns laser pulse at 532 nm and the scattered light is detected by a gated ICCD camera connected to a TGS. Up to three orders of magnitude dynamic range for the absolutely calibrated EVDF are archived in the range 0.5 eV to 12 eV. A 60 ns Townsend pre-phase is followed by a 90 ns long DC-like discharge showing strong atomic emission lines. The 1,000 ns long afterglow is characterized by initial recombination of cold electrons and Helium excimer formation, predominately in Rydberg states, which slowly relax to lower states radiating in the visible range of the spectrum. Rydberg states are probed by ionization with an intense laser pulse and subsequent detection of the additional free electrons by Thomson scattering. This work was funded by the DFG Research Group FOR1123.

10:45

TF4 3 Influence of HV pulse repetition rate on densities of excited species in atmospheric helium plasma jet* NADER SADEGHI, *LTM & LIPhy, Univ. Grenoble & CNRS, France* VINCENT PUECH, CLAIRE DOUAT, *LPGP, Univ. Paris-Sud & CNRS, France* Time varying plasma characteristics of a 2 mm diameter atmospheric helium microplasma jet excited by nanosecond high voltage pulses (4-7 kV; 1-50 kHz rep. rate) was studied. Density of helium He(2^3S_1) metastable atoms was determined by tunable laser diode absorption. The spatio-temporal dynamics of characteristic plasma jet emissions, such as the 706.5 nm and 587.5 nm He* and 777 nm O* lines, the 337 nm N_2(C-B), 391 nm N_2^+(B-A) and 308 nm OH* bands were studied by sub-nanosecond time-resolved imaging of the jet with bandpass filters and by nanosecond time-resolved photon-counting behind an spectrograph. Spatial distribution of excited species strongly depends on plasma parameters and HV pulses rep. rate; *e.g.* hollow shape profiles at 3 kHz become axially centered above 10 kHz. Also, higher is the rep. rate slower are the late afterglow decay times of O* and OH* emissions, reaching about 20 μs at 20 kHz. This is likely linked to the very slow positive ion-negative ion recombination mechanism, producing these excited species. The two above-mentioned effects are attributed to a memory effect due to formation of negative ions generated from water impurity and air penetration.

*Supported by French ANR grant PAMPA.

11:00

TF4 4 Comparison between micro hollow cathode discharges and atmospheric pressure plasma jets working in Ar/O_2 CLAUDIA LAZZARONI, *LSPM-CNRS, Institut Galilee, Universite Sorbonne Paris Cite, Universite Paris 13* PASCAL CHABERT, *LPP-CNRS, Ecole Polytechnique, UPMC, Universite Paris 11* MP4 (LSPM) TEAM, PLASMAS FROIDS (LPP) TEAM A global model of a Micro Hollow Cathode Discharge (MHCD) in argon (Ar) with an admixture of oxygen (O_2), working at several hundreds of Torr, is presented. MHCDs operate in steady state and in self-pulsed mode both captured by the model. This discharge is a source of high reactive oxygen species (ROS) densities, a key parameter in many applications such as medicine. The Atmospheric Pressure Plasma Jet (APPJ), which consists in the application of a radio frequency (RF) voltage across two parallel electrodes separated by one millimeter, is another micro-plasma source which is widely used in medicine. The global model of the MHCD is compared to an analytical-numerical global model of the APPJ. Seventeen species are considered and 130 reactions are taken into account in the plasma volume. The species densities oscillate in time during the self-pulsing regime of the MHCD, following the discharge current oscillations, and we will compare the peak and the time-averaged densities to the APPJ densities. This comparison shows that in both regimes, the MHCD produces preferentially reactive oxygen excited species, O* and O_2*, whereas the APPJ produces preferentially reactive oxygen stable species, O and O_3. This is due to the higher plasma densities produced in the MHCD.

11:15

TF4 5 Gas and heat dynamics of a micro-scaled atmospheric pressure plasma jet* JUDITH GOLDA, *Ruhr-Universitaet Bochum, Experimental Physics II, 44801 Bochum, Germany* SEAN KELLY, MILES M. TURNER, *School of Physical Science and National Centre for Plasma Science and Technology, Dublin City University, Dublin, Ireland* VOLKER SCHULZ-VON DER GATHEN, *Ruhr-Universitaet Bochum, Experimental Physics II, 44801 Bochum, Germany* Low temperature atmospheric pressure plasma jets enable the production of reactive species. Therefore, they are used for surface modification and considered for use in biomedicine. Bio-medical applications demand stability of the discharge and knowledge of the temperature of the plasma effluent and the device components. While treating heat-sensitive biological material, the threshold temperature of the tissue must not be exceeded. Additionally, chemical processes in the discharge strongly depend on the gas temperature. However, heating in such discharges is still poorly understood. To assess this problem, we investigated the geometric design of the microscaled atmospheric pressure plasma jet based on a reference jet which is proposed by the European COST group MP1101. Thermocouple measurements and numerical model data show a bounded exponential temperature growth described by a single characteristic time parameter. Where the carrier gas exits the device, peak temperatures range from 297 K to 381 K in "alpha mode" operation for flows of 2 - 0.25 slpm. Spatial profiles of surface heating, obtained by thermal imaging, are found to correlate strongly with the impacting plume where peak temperatures occur in regions of maximum surface helium concentration.

*This work was supported by the Ruhr University Research School PLUS, funded by Germany's Excellence Initiative [DFG GSC 98/3] and PlaCiD SCHU-2323/3-1.

11:30

TF4 6 Properties of DC-Pulsed Microplasma Arrays at Intermediate Pressures* PENG TIAN, CHENHUI QU, MARK J. KUSHNER, *University of Michigan* Microplasma arrays are being investigated to manipulate electromagnetic waves due to their ability to change electrical properties with a short response time. In these applications, there are often tradeoffs between a short response time, plasma density and uniformity of the plasma, all of which scale with pressure. Controlling of cross-talk between microdischarges is also an issue when there are no physical isolations between microdischarges in the array. These scalings motivate operation at intermediate pressures, 10s to 100s Torr, which by pd scaling corresponds to sizes of the microcavity of hundreds of microns. In this paper, a computational investigation on the scaling of microplasma arrays excited by pulsed dc-bipolar/unipolar waveforms is discussed using results from a 2-dimensional plasma hydrodynamics model. The goal is to maximize the time averaged electron density in a spatially controllable manner while controlling cross-talk between microplasmas that are not physically isolated. We investigated 1-D and 2-D microplasma arrays of sub-mm cavities operating at 10s-100s Torr in rare gases, excited by ns DC pulses with several MHz pulsing frequency. Plasma densities up to 10^{14} cm^{-3} are predicted in Penning mixtures.

*Work supported by DARPA, DOE (DE-SC0001319), and NSF (CHE-1124724).

11:45

TF4 7 Phase-resolved imaging of the interaction dynamics in rf-driven microplasma arrays at atmospheric pressure* JEROME BREDIN, KATHARINA GROSSE, *York Plasma Institute, Department of Physics, University of York* SAMEER AL-BATAINEH, ENDRE SZILI, ROB SHORT, *Mawson Institute, University of South Australia* DEBORAH O'CONNELL, *York Plasma Institute, Department of Physics, University of York* Atmospheric-pressure microplasmas are under development for future surface processing applications due to their decreased cost and high throughput compared to low-pressure configurations. Microplasma arrays are designed to achieve a large-area homogenous treatment. The investigated plasma source consists of a 7x7 micron-scale dielectric barrier discharges array operated in an atmospheric-pressure helium environment. The discharge is driven by radio-frequency (rf) power at 2 MHz and the power is pulsed at 1 kHz with an on-time of 90 rf cycles. Pulsed rf offers promise of improved control over the plasma properties and long operation lifetimes of the arrays. Nanosecond imaging (head-on and side observation) is used to investigate the spatio-temporal behaviour and the interactions between the cavities throughout the pulse. As a function of time within the pulse, distinct plasma dynamics are observed. This includes the formation of "glow" and "ring" shaped discharges as well as interactions between discharges. These depend on the dimensions of the cavities and the driving voltage. Through this study, we expect to be able to tailor conditions such as homogeneous operation and optimum species production.

*Financial support was received from the UK EPSRC (EP/K018388/1 & EP/H003797/1).

SESSION UF1: PLASMA SOURCES FOR BIOMEDICAL APPLICATIONS II
Friday Afternoon, 16 October 2015; Room: 301 B at 13:30; Stephan Reuter, INP Greifswald, presiding

Invited Papers

13:30

UF1 1 Atmospheric non-equilibrium plasma sources and processes with a focus on plasma medicine & antibacterial applications*

VITTORIO COLOMBO, *Alma Mater Studiorum - Università di Bologna, Department of Industrial Engineering - Italy*

Non-equilibrium atmospheric pressure plasmas (NTPs) offer an astounding versatility, relying on a wide range of physical principles and source architectures for their generation and sustainment; spanning from DBDs to plasma guns, from jet-to-jet coupled sources to hot plasmas at the production site. NTPs are being explored for an ever increasing number of biomedical and therapeutic applications. The talk will mainly consider the following subjects: investigation of the antimicrobial activity of a low power ICP source at safe levels for eukaryotic cells; investigation of antibacterial efficacy of a plasma gun source for endodontic applications; antimicrobial activity induced in static water by a DBD reactor driven by nanosecond pulses. Some preliminary results will also be given for in vivo investigation on the effects of plasma activated water against plant pathogenic bacteria and for the study on the effectiveness of a jet-to-jet coupled nanopulsed source for localized bacterial inactivation. In collaboration with Daniela Barbieri, Marco Boselli, Matteo Gherardi, Romolo Laurita, Anna Liguori, Emanuele Simoncelli, Augusto Stancampiano, and Enrico Traldi, Alma Mater Studiorum - Università di Bologna, Department of Industrial Engineering - Italy.

*Work partially supported AlmaPlasma s.r.l., by COST Action MP1101 "Biomedical Applications of Atmospheric Pressure Plasma Technology" and by COST Action TD1208 "Electrical discharges with liquids for future applications."

Contributed Papers

14:00

UF1 2 Development of an innovative low temperature DBD plasma source based on a flexible textile layer for medical applications J.-S. BAUDLER, S. HORN, A. QUADE, K.-D. WELTMANN, *INP Greifswald e.V.* Plasma sources for medical applications are usually expensive and inconvenient due to big dimensions or the need for special infrastructure. Our approach is to design a plasma source which will not only solve these problems, so it can also be mass produced at comparatively small costs. this presentation we will show a short overview about the whole development process of such a device. We will start with the idea, including CAD, electric field simulation and proof of concept. Afterwards we will proceed to the prototype design and manufacturing including material choice, electrical control and conducting the first antimicrobial tests. The most important role during the development was the choice of materials for the dielectric barrier. The barrier is responsible for several important factors like required voltage, system capacity and user security. We will show that the class of fluoropolymers is one of the best choices here, but with the risk of harmful degradation products. Due to medical restrictions we had to look after these products with the widely used PTFE in mind. To estimate this risk we have used VUV-Spectroscopy to look in-vivo after the creation of the ArF excimer as a relative indicator for the degradation processes. When we observed this indicator we searched for ways to lower the risk. We ended up with two possible solutions: the defluorisation of the surface and lowering the overall system energy by electrode design. We compared both with our initial results to estimate the effectiveness of the methods.

14:15

UF1 3 Interaction of AC excited Atmospheric Pressure Ar Plasma Jet with Medium* KEIGO TAKEDA, SIJIE LIANG, TAKUMI KUMAKURA, KENJI ISHIKAWA, HIROMASA TANAKA, MAKOTO SEKINE, MASARU HORI, *Nagoya Univ* Recently, there are interesting results on the plasma selective killing of cancer cells against normal cells using the atmospheric pressure plasma. In the applications, the interaction of plasma with liquid is a hot research topic since most cells and tissues are surrounded by liquids. In the cases, reactive species in gas phase play important roles on the generation of reactive species in the medium. Therefore, it is strongly required to diagnose the behaviors of gas-phase reactive species for clarification of the interactive reactions of plasma jet with the medium. In this study, the interaction of an AC excited argon atmospheric pressure plasma jet (APPJ) with medium have been investigated on the basis of behaviors of gas-phase OH radical measured by using optical emission spectroscopy and laser induced spectroscopy. From the results, the OH radical was observed only in the plasma jet for irradiating the medium with the plasma jet. Therefore, in the AC excited APPJ treatment, it is considered that OH radical is mainly generated by dissociation of water vapor in ambient air and the effects of OH radical on generation of reactive species in the medium decreased with increase in the distance between plasma head and medium surface.

*This work was supported by a Grant-in-Aid for Scientific Research on Innovative Areas Plasma Medical Innovation under Grant 24108002.

Invited Papers

14:30

UF1 4 Long-Term Preservation of Marine Products via Conformational Change of Protein by Electrostatic Effect
KOICHI TAKAKI, *Iwate University*

Conformational change of Bovine Serum Albumin (BSA) by AC electric field was studied experimentally for long-term preservation of marine products. The AC voltage was generated with a transformer that had an amplitude of 10 kV and a frequency of 50 Hz. High AC voltage was applied to a metal shelf located in an incubator. The experimental results suggested that the conformation of protein changed from α-helix to β-sheet by applying AC voltage during the preservation. The denaturation of the protein with the temperature change was suppressed by the AC voltage treatment. The AC electric field was also applied during freezing to improve the freshness. Both sample groups were cryopreserved and placed in each incubator at -10 °C for 20 days. The freshness was estimated by the amount of the proteins with the molecular weight of less than 70,000 included in the drip which eluted from samples called SDS polyacrylamide gel electrophoresis. It was found that the amount of the protein with the molecular weight of less than 70,000 decreased by applying the AC high voltage. The degeneration in proteins was inhibited by the effect of the AC high voltage. This experimental results showed that the use of AC voltage during freezing is effective for preserving the freshness of the perishable foods. In collaboration with Takanori Ito, Takamasa Okumura, Katsuyuki Takahashi, Sumio Aisawa, Shigeyoshi Yamazaki, and Bunei Syuto, Iwate University.

SESSION UF2: DIFFUSE DISCHARGES
Friday Afternoon, 16 October 2015; Room: 308 AB at 13:30; Thomas Miller, Boston College, presiding

Invited Papers

13:30

UF2 1 Operating modes of a low pressure, high current, magnetized rare-gas plasma*
DAVID SMITH, *General Electric*

We have investigated high current operation of a magnetically-enhanced rare-gas plasma for use as a high-voltage, high-power gas switch in grid-scale electric power conversion. It is desirable to operate at a low voltage to minimize incident ion energy and reduce the cathode erosion rate by sputtering. We have determined the key characteristics of low-voltage mode operation by correlating the electrical pulse and optical emission spectroscopy data with observations from high-speed movies. We have identified four key modes of operation, namely magnetron mode (200-300 V), a constricted, rotating mode (70-120 V), an edge-enhanced constricted mode (40-60 V), and metal/arc mode (20-40 V), along with the cathode geometry and the operating conditions required to select the desirable modes. It is essential to minimize operation time in either magnetron mode or metal mode due to the high erosion rate of cathode material in each case. The edge-enhanced constricted mode has a favorably low voltage but is characterized by the plasma attaching to sharp/rough surface features. The constricted, rotating mode is the preferred operating regime due to low voltage losses and the absence of cathode material observed in optical emission spectra.

*The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

Contributed Papers

14:00

UF2 2 Ionization instabilities of plasma column at high electromagnetic field frequencies SERGEY DVININ, *Lomonosov Moscow State university* VITALY DOVZHENKO, *Obukhov Institute of Atmospheric Physics RAS* OLEG SINKEVICH, *National Research University Moscow Power Engineering Institute* The stability problem of spatially limited high frequency plasma discharge is analyzed. This instability breaks the spatial plasma homogeneity and leads to forming of complex spatial structures. In traditional works its development is associated with the kinetic processes in plasma [1] and the total electric current is conserved. Here the exact solution of Maxwell's equations in the form of a series is found. The solution takes into account both potential and vortex perturbation. A separate solution contains the field, associated with conversation law, as separate term. It is shown that the traditional approach can only be used far from electrodynamic resonances of the plasma. For plasma without a magnetic field the resonances are associated with the surface waves. Instability increments for different ratios of the collision frequency to the frequency of the field are found. The phenomenological model, that describes nonlinear stage of instability and new stationary state, is proposed. Satisfactory agreements between theory and experiment [2] are obtained. We demonstrate that the ionization instability, leading to the appearance of plasma inhomogeneity, can be observed in any discharge system, when several types of electromagnetic waves can propagate simultaneously.

[1]D. Mackey, L. Plantié, and M. M. Turner, Appl. Math. Lett. **18**, 865 (2005).
[2]S. Dvinin *et al.*, Sov. Phys.: Fizika Plazmy **9**, 1297 (1983).

14:15

UF2 3 Effect of gas pressure on subnanosecond current front rise in high-voltage pulse open discharge: experiment and simulation* I.V. SCHWEIGERT, *The George Washington University, Washington DC, USA* A.L. ALEXANDROV, *Khristianovich Institute of Theoretical and Applied Mechanics, Novosibirsk, Russia* DM. E. ZAKREVSKY, P.A. BOKHAN, *A.V. Rzhanov Institute of Semiconductor Physics, Novosibirsk, Russia* The subnanosecond development of breakdown was observed in helium in high-voltage open discharge in experiment [1]. The voltage pulse of 20 kV is applied to two cathodes, placed symmetrically at 3 mm on both sides of a grid anode with high transparency for gas pressure from 3 to 15 Torr. The breakdown current develops for the time less than 1 ns. The mechanism of such efficient generation of electron avalanche is explained by photoemission by photons, produced by atoms, excited by impact of ion or fast neutral atom. Such photons have Doppler-shifted frequency and propagate to cathodes without reabsorption. The kinetic model of breakdown includes electrons, ions and fast atoms generation and motion, with 11 reactions with background gas [2]. The kinetic equations are solved by PIC MCC method self-consistently with Poisson equation. Also the cathode emission by heavy particles is accounted. The simulations show the breakdown time from 0.2 to 0.5 ns, decreasing with pressure growth, which is in good agreement with the experimental results.

*We are grateful to the Russian Science Foundation for supporting this work, project 14-19-00339.

[1]P. A. Bokhan, P. P. Gugin, M. A. Lavrukhin, and Dm. E. Zakrevsky, Phys. Plasma **20**, 033507 (2013).
[2]I. V. Schweigert, A. L. Alexandrov, P. A. Bokhan, and Dm. E. Zakrevsky, Phys. Rev. E **90**, 051101 (R) (2014); Plasma Sources Sci. Technol., 2015, accepted.

14:30

UF2 4 DC Non-thermal Atmospheric-pressure Plasma Jet Generated by Syringe Needle Electrode KHANIT MATRA, *Srinakharinwirot University* In this paper, non-thermal plasma jet operated in the atmospheric-pressure environment is presented. Plasma jet is generated by applying dc source voltage between 1.2 mm of inner diameter syringe needle anode with flowing Argon gas and planar or hollow copper cathode. Two operating discharge modes, which are self-pulsing discharge and continuous discharge mode, are mainly controlled by the limitation of current flowing in the discharge circuit. Rated current flowing in the circuit and ballast resistor (800 kiloohm and 1 Megaohm ballast resistors are chosen in this research) are important factors affecting on the limitation of operating discharge mode. Gas breakdown are initially generated in the self-pulsing discharge mode at the source voltage of 1.2 kV, which is slightly higher than the breakdown voltage, at the experimental condition of Argon gas flow rate of 1 LPM and electrode gap distance of 1 mm. The self-pulsing discharge currents are up to 15-20 amperes with self-pulsing frequency in the range of 10-20 kHz. The continuous discharge mode could be observed at the higher source voltage, compared with those of self-pulsing discharge mode, with the continuous discharge current in the range of a few milliamperes.

14:45

UF2 5 Plasma generated VUV in a microwave surface-wave plasma JIANPING ZHAO, MERRITT FUNK, LEE CHEN, *Tokyo Electron America* KOJI KOYAMA, TOSHIHISA NOZAWA, *Tokyo Electron Limited* SEIJI SAMUKAWA, *Tohoku University* TOKYO ELECTRON AMERICA TEAM, TOKYO ELECTRON LIMITED COLLABORATION, TOHOKU UNIVERSITY COLLABORATION Vacuum ultraviolet (VUV) radiations generated in low temperature plasmas has been reported to cause device damage, alteration of morphology of polymers and electrical properties of dielectrics. In order to improve the device and plasma process reliability, monitoring and evaluation of plasma generated VUV radiations have become important and highly demanded in plasma processing. Herein, characterization of VUV radiations generated in a microwave surface-wave plasma is reported. The plasma source used in this work transmits 2.45 GHz microwaves into a large quartz resonator disk which then couples to the plasma. VUV radiations from the plasma are monitored by measuring VUV induced electron-hole pair generation in dielectric film based VUV sensors. Measurements in N2, Ar, and O2 plasma are carried out as a function of distance from the plasma generation region. For better understanding on the evolution of plasma VUV, VUV radiations from an inductively coupled plasma is also investigated. Mechanisms on the VUV evolution are discussed based on the measured electron energy distribution functions (EEDFs) and VUV absorption process.

SESSION UF3: NONEQUILIBRIUM KINETICS OF LOW-TEMPERATURE PLASMAS

Friday Afternoon, 16 October 2015
Room: 305 AB at 13:30
Julian Schulze, West Virginia University, presiding

Contributed Papers

13:30

UF3 1 Discussion on Electron Temperature of Low-Pressure Discharge Oxygen Plasma with Non-Maxwellian EEDF Based on Statistical Physics HIROSHI AKATSUKA, YOSHINORI TANAKA, *Tokyo Institute of Technology* We reconsider electron temperature of non-equilibrium oxygen plasmas based on thermodynamics and statistical physics by the relationship between entropy and mean energy of electron gas. First, we solve the Boltzmann equation to obtain electron energy distribution function (EEDF) $F(\epsilon)$ of the oxygen plasma for a given reduced electric field E/N. We also simultaneously solve kinetic equations to determine some essential excited species in the oxygen plasma, since the EEDF should be self-consistently solved with the densities of collision partners. Next, we calculate the electron mean electron energy $U = \langle\epsilon\rangle = \int_0^\infty \epsilon F(\epsilon)\mathrm{d}\epsilon$ and entropy $S = -k\int_0^\infty F(\epsilon)ln[F(\epsilon)]\mathrm{d}\epsilon$ for each value of the reduced electric field E/N. Then, we can obtain the electron temperature calculated as $T_e^{th} = [\partial S/\partial U]^{-1}$. After that, we discuss the difference between T_e^{th} and the kinetic temperature $T_e^k \equiv (2/3)\langle\epsilon\rangle$, as well as the temperature given as a slope of the calculated EEDF for each value of E/N from the viewpoint of statistical physics as well as elementary processes.

13:45

UF3 2 Influences of electron-electron and metastable collisions in electrical breakdown of air JOHN LOWKE, EUGENE TAM, ANTHONY MURPHY, *CSIRO-Manufacturing* To predict the time development of electrical breakdown in air accurately, detailed knowledge is required of the dominant ionization processes that occur between initial ionization, which requires an electric field of ~ 25 kV/cm at 1 bar, and the final arc stage, which can be maintained by electric fields of only ~ 20 V/cm. This paper discusses two collision processes which increase ionization by changing the energy distribution function of the electrons. At 5 kV/cm at 1 bar, there are effectively zero electrons at high enough energies to produce ionization, so the ionization coefficient is zero, largely due to the large energy losses of electrons exciting the many vibrational states of nitrogen. This situation is markedly changed by collision processes that make the energy distribution more Maxwellian, introducing more electrons at ionization energies. One such process is electron-electron collisions, which can dominate for high degrees of ionization of the air. It is shown that this process can increase streamer speeds and lengths about a factor of two. A second process is the presence of large populations of metastable states, for example of nitrogen vibrational states, which can increase electron energies by electrons de-exciting these states. But the electric field and discharge times need to be large enough to allow for the development of sufficient population densities of these states. The discharge development times appear to be not large enough to explain lightning initiation at low fields.

14:00

UF3 3 Modelling the influence of neutral gas heating mechanisms on particle densities in inductively coupled chlorine discharges* ANDREW GIBSON, *LPP-CNRS and University of York* TIMO GANS, *University of York* MICKAEL FOUCHER, DANIIL MARINOV, PASCAL CHABERT, *LPP-CNRS* VASCO GUERRA, *IPFN/IST-UTL* MARK KUSHNER, *University of Michigan* JEAN-PAUL BOOTH, *LPP-CNRS* Inductively coupled plasmas produced in reactive electronegative gases, such as chlorine (Cl2), are commonly used for the etching of nanometre scale structures in the semiconductor industry. However, despite their widespread usage, the dominant energy transport mechanisms in these systems are often not well known. In particular, neutral gas heating is an important factor in determining many plasma parameters, such as the densities of electrons or atomic chlorine radicals (Cl). In this context the dissipation of electron energy by collisions with neutral species, for example through Franck-Condon heating or indirectly by vibrational excitation followed by v-t transfer, is of key importance. In this study the influence of such heating mechanisms on important species densities has been investigated using the Hybrid Plasma Equipment Model (HPEM). By comparison with experimental data, it is found that the electron density can be underestimated and its radial profile poorly reproduced if the proper heat transfer mechanisms are not included in the model. This in turn has important effects on other plasma parameters, such as the charged and neutral particle densities. The inclusion of both Franck-Condon heating and v-t transfer significantly improves agreement with experimental data.

*This work received funding from UK EPSRC Grant (EP/K018388/1) and financial state aid managed by the laboratory of excellence Plas@Par (ANR-11-IDEX-0004-02).

14:15

UF3 4 Controlling the Electron Energy Distribution Function Using a Biased Electrode* SCOTT BAALRUD, *Univ of Iowa* BENJAMIN YEE, MATTHEW M. HOPKINS, EDWARD V. BARNAT, *Sandia National Laboratory* Positively biased electrodes inserted into plasmas influence the EEDF by providing a sink for low energy electrons that would otherwise be trapped by ion sheaths at the chamber walls. In hot filament generated discharges, the EEDF is nominally characterized by a cool trapped population at energies below the sheath energy and a comparatively warm tail population associated with the filament primaries. Inserting a positively biased electrode has little influence if it is so small that it collects a negligible fraction of the total electron current exiting the plasma. However, as the electrode area approaches $\sqrt{2.3m_e/m_i}A_w$, where A_w is the chamber wall area, it collects most of the electrons leaving the plasma. This drastically reduces the density of the otherwise trapped population, and causes the electron temperature to increase as the distribution approaches a temperature associated with the energetic filament primaries. A global model is developed based on current and power balance, which shows the interconnected nature of the electron temperature, density and the plasma potential. This model is compared with Langmuir probe measurements in a dc filament generated plasma [1], and with 2D PIC simulations.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contract DE-AC04-94SL85000.

[1]Barnat, Laity, and Baalrud, Phys. Plasmas **21**, 103512 (2014).

14:30

UF3 5 Global model of oxygen plasmas: A benchmark study and the role of the vibrational quanta of O_2* EFE KEMANECI, *Ruhr University Bochum* JAN VAN DIJK, *Eindhoven University of Technology* THOMAS MUSSENBROCK, RALF BRINKMANN, *Ruhr University Bochum* INSTITUTE FOR THEORETICAL ELECTRICAL ENGINEERING COLLABORATION, DEPARTMENT OF APPLIED PHYSICS COLLABORATION Oxygen plasmas are investigated based on a global modelling approach with a focus on the inductive radio-frequency discharges in both continuous and pulse-modulated modes. A throughout benchmark study is performed mainly with respect to the experimental data available in literature. The experimental data is preferred to cover a wide range of energy coupling modes: (asymmetric) capacitive, inductive as well as microwave modes; and an agreement is obtained in both continuous and pulse-modulated power inputs. In a benchmark case of a microwave-induced reactor plasma, a spatially-resolved plasma fluid model is also developed that is self-consistently coupled to the microwave propagation and the data is compared with the results of the corresponding global model simulation. The role of the vibrational quantum levels of molecular oxygen is analysed, where a set of chemical kinetics is proposed. The chemical kinetics includes 41 vibrational quanta as well as the e-V, V-V and V-T interactions. A ladder-like dissociation mechanism is also incorporated, where the highest vibrational quanta are set to be a pseudo-level and it is assumed to dissociate immediately.

*Deutsch Bundesministerium fur Bildung und Forschung via PluTO+

14:45

UF3 6 Revisiting Pierce Instability: Bandwidth Structure of Growth Rate of Two-Stream Instability of an Electron Beam Propagating in a Bounded Plasma IGOR D. KAGANOVICH, *Princeton University* DMYTRO SYDORENKO, *University of Alberta, Canada* The two-stream instability of an electron beam propagating in finite-size plasma placed between two electrodes is studied analytically and numerically. It is shown that the growth rate in such a system is much smaller than that of infinite plasma or finite size plasma with periodic boundary conditions. We show that even if width of the plasma matches the resonance condition for standing waves; standing waves do not develop and transform into spatially growing wave, whose growth rate is small compared to that of the standing wave in a system with periodic boundary conditions; this growth rate is approximately described by $\gamma \approx 1/13\omega_{pe}(n_b/n_p)(L\omega_{pc}/v_b)\ln(L\omega_{pc}/v_b)$, where ω_{pe} is the electron plasma frequency, n_b and n_p are beam and plasma densities, respectively, and v_b is the beam velocity, L is the plasma width. The frequency and growth rate as a function of plasma width form a bandwidth structure.

SESSION UF4: HEAVY-PARTICLE COLLISIONS AND SWARMS

Friday Afternoon, 16 October 2015; Room: 303 AB at 13:30; Michael Schulz, Missouri University of Science and Technology, presiding

Invited Papers

13:30

UF4 1 Biomolecular Ionization and Fragmentation Dynamics after Interaction with keV Ions and Energetic Photons
THOMAS SCHLATHOELTER, *University of Groningen, The Netherlands*

14:00

UF4 2 An independent-atom-model description of ion-molecule collisions including geometric screening corrections*
TOM KIRCHNER,† *York University*

A simple way of calculating charged-particle-induced electron removal cross sections for molecular targets consists in adding up atomic cross sections for all the atoms that make up the molecule. This procedure is commonly referred to as Bragg's additivity rule (AR) and is based on the independent-atom model, in which the molecule is viewed as a collection of (undistorted) atoms. The AR works well at sufficiently high collision energies, where the atomic cross sections tend to be small. For electron-molecule collisions several extensions of the AR have been proposed to make it applicable to lower impact energies, where the atomic cross sections are large and the AR results in an overestimation of the experimental data. One such extension is the so-called screening-corrected additivity rule (SCAR) [1]. For each atomic cross section σ_A in the AR a weight factor $0 \leqslant s_A \leqslant 1$ is introduced to account for the partial screening of the atoms due to the geometrical overlap of the σ_A's when viewed from the incident electron. The weight factors are determined heuristically and are interpreted as orientation-averaged screening coefficients. In this contribution, we propose a similar model for net ionization and electron transfer in heavy-particle collisions, but in contrast to the SCAR model the weight factors do depend on the orientation of the molecule relative to the projectile beam direction. For a given geometry we construct a space-filling-like model of the molecule by surrounding each atom A by a sphere of radius $r_A = \sqrt{\sigma_A/\pi}$. The weight factors in the SCAR-like cross section formula are determined as those fractions of the σ_A's that are visible for an observer that moves with the impinging projectile. The procedure is repeated for a number of molecular orientations, and total cross sections that can be compared with experimental data are obtained by averaging over all orientations. The atomic cross sections are calculated by using the two-center basis generator method [2], while the molecular geometry information that enters the calculation of the screening coefficients is taken from the literature, In my talk, I will explain the model in more detail and will present total cross section results for proton collisions from a number of targets ranging from diatomic molecules such as H_2 and CO to intermediate-size hydrocarbons such as butane.

*Work supported by NSERC, Canada.

†In collaboration with Hans Jürgen Lüdde, Goethe University Frankfurt and Marko Horbatsch, York University.

[1] F. Blanco *et al.*, Phys. Lett. A **374**, 4420 (2010).
[2] M. Zapukhlyak *et al.*, J. Phys. B **38**, 2353 (2005).

Contributed Papers

14:30

UF4 3 Electron swarm from very low to intermediate E/N in homonuclear diatomic molecules H_2, O_2 and N_2* M.A. RIDENTI, *Departamento de Física, Instituto Tecnológico de Aeronáutica* L.L. ALVES, V. GUERRA, *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa* J. AMORIM, *Departamento de Física, Instituto Tecnológico de Aeronáutica* In this work the homogeneous Boltzmann equation is solved in order to describe the electron swarm in N_2, O_2 and H_2 within the interval $10^{-4} - 10$ Td. Elastic, rotational and vibrational collisions are taken into account and it is shown how each of these channels contributes to the electron energy balance as a function of E/N. Three different approaches are adopted to account for the rotational collisions. The first one, which gives the most accurate results, consists of computing the discrete inelastic / superelastic collisional operator, written for a number of rotational levels that depends on the molecular gas and the specific rotational cross sections considered. The second approach is the continuous approximation for rotations, as proposed by the classical work of Frost and Phelps (Phys. Rev. 1962). The last approach is a modified version of the continuous approximation for rotations, including a Chapman-Cowling corrective term proportional to the gas temperature, which is deduced here. Results from this last approach show that it may be used to bridge the gap between the discrete and the continuous descriptions at low/intermediate E/N. The calculations are compared with measurements for the available swarm parameters.

*CAPES, under processes 0467-13-8 and 005/2014; Fundação para a Ciência e a Tecnologia, under Project Pest-OE/SADG/LA0010/2013.

14:45

UF4 4 Measurement of negative ion mobility varying with a little amount of H_2O in O_2 YUI OKUYAMA, SUSUMU SUZUKI, HARUO ITOH, *Chiba Institute of Technology* A study of transport properties such as a mobility of charged particles is importance in understanding discharge plasmas. These fundamental data have been collected in some databases. The authors have been investigated the effects of impurities such as H_2O, CO_2, N_2 on the negative ion mobility in O_2 at high pressures including atmospheric pressure [1, 2]. Especially, the effect of a trace amount of H_2O in O_2 could not to be avoided for the mobility measurement due to formation of cluster ions $O_2^- \cdot (H_2O)_n$ (n = 1, 2, 3, ...). In this study, the mobility of negative ions was measured in O_2 varying with the H_2O concentration from 100 to 17000 ppb. The H_2O concentration was monitored with a trace moisture analyzer whose operation was based on a photoabsorption method. As the results, a constant mobility of 2.39 $cm^2/V \cdot s$ was observed in ultrahigh-purity O_2 (99.99995%, purified with a gas purifier), in which the H_2O concentration was monitored to be between 15 and 100 ppb. This value was good agreement with the mobility of O_4^- in previous report [1]. Then, a small amount of H_2O from 2000 to 17000 ppb was added to the ultrahigh-purity O_2. Two kinds of mobilities 2.31 and 2.21 $cm^2/V \cdot s$ were observed in H_2O concentration ranges of 2000 - 4600 and 4600 - 17000 ppb, respectively. Former one is good agreement with the mobility observed in high-purity O_2 (99.9999%) [2]. These mobilities are considered to be those of $O_2^- \cdot (H_2O)_n$ (n = 1, 2).

[1]Y. Okuyama *et al.*, 66th Annual Gaseous Electronic Conference, 57, 8, MR1.00091 (2013).
[2]Y. Okuyama *et al.*, J. Phys. D: Appl. Phys. **45**, 195202 (2012).

SESSION WF1: PLASMA THRUSTERS AND FLOW CONTROL

Friday Afternoon, 16 October 2015
Room: 301 B at 15:30
John Foster, University of Michigan, presiding

Contributed Papers

15:30

WF1 1 Modelling the plasma in the helicon source of a helicon plasma thruster* AMNON FRUCHTMAN, *H.I.T. - Holon Institute of Technology* A quasi-two-dimensional model of the helicon plasma source is presented. The model is an extension of our previously published one-dimensional model, to also include wall losses. Wall losses result from radial transport of the plasma across the confining magnetic field. Electrons cross magnetic field lines due to collisions. Three types of collisions are taken into account: electron-neutral collisions, electron-ion collisions, and effective anomalous collisionality that is independent of both ion and neutral densities. The equations will be derived for a polytropic equation of state of the electrons. With the assumption that the electrons are isothermal, an analytical solution is derived for the axial dependence of the plasma and neutral variables along the plasma source. An algebraic expression relates the propellant utilization to the electron temperature and the various electron collision frequencies. Asymptotic expressions for the propellant utilization are derived for low and high propellant utilizations. An analysis of the magnetic nozzle should be added to this analysis of the helicon source in order to have a complete model of the helicon plasma thruster.

*This research was partially supported by the Israel Science Foundation, Grant No. 765/11.

15:45

WF1 2 Ion Acceleration Modes in a Miniature Helicon Thruster TIMOTHY A. COLLARD, FRANS H. EBERSOHN, J.P. SHEEHAN, *University of Michigan* Operation and characterization of the CubeSat Ambipolar Thruster (CAT), a miniature helicon electric propulsion device, is presented. Its small plasma volume ($\sim 10\ cm^3$) and low power requirements (<100 W) make it ideal for propelling nanosatellites (<10 kg). Permanent magnets generated a magnetic nozzle with a maximum field strength of 800 G. This field decreased to 0.5 G, the strength of earth's magnetic field, within 50 cm allowing the entire exhaust plume to develop in the vacuum chamber without being affected by the chamber walls. A parametric study of the thruster operational parameters was performed to determine its capabilities as both a thruster and as a plasma source for magnetic nozzle experiments. Operating with xenon and argon, separately, the plasma density, electron temperature, and plasma potential in the plume were measured with Langmuir probes, double probes, and emissive probes. Two modes of operation were observed. At low flow rates ($\sim$ 5 sccm) the plasma was well collimated along the magnetic nozzle and produced beam ions in excess of 50 eV. At high flow rates ($\sim$ 25 sccm) charge exchange collisions disrupted the magnetic nozzle and no ion beam was observed.

16:00

WF1 3 A fully 2D electron fluid model for Hall thrusters* HORATIU DRAGNEA, KENTARO HARA, IAIN BOYD, *Univ of Michigan - Ann Arbor* A Hall thruster is a cross-field device used for spacecraft propulsion. Recent Hall thruster developments, such as magnetic shielding and nested channels, have prompted the need to improve simulation capabilities. State-of-the-art hybrid methods such as HPHall [Fife, PhD MIT, 1998] employ a quasi-1D fluid electron model, which decouples the electron transport along and across the magnetic field lines. However, this approach cannot be used for complex magnetic field topologies, or extended computational domains. In this study, we present a fully 2D fluid electron model that directly captures the multidimensional electron transport in complex magnetic field configurations. More specifically, the plasma potential is calculated by solving a 2^{nd} order partial differential equation obtained from the generalized Ohm's law for electrons in conjunction with the charge conservation equation, and assuming a quasineutral plasma. A 9-point Cartesian stencil is used to capture the effects introduced by the cross-terms and a thruster channel test case is constructed assuming dielectric channel walls as well as an anode and cathode. We present test cases under several magnetic field configurations in comparison with previous modeling results [Geng *et al.*, JAP, 2013], and a quasi-1D model.

*This work was supported by a NASA Space Technology Research Fellowship.

16:15

WF1 4 Water-based Electric Propulsion for Small Spacecraft* JOHN SLOUGH, *University of Washington* JUSTIN LITTLE, ANTHONY PANCOTTI, *MSNW LLC* JORDAN NEUHOFF, *University of Washington* AEROSPACE PROPULSION GROUP COLLABORATION In-space micropropulsion systems must strike a balance between simplicity, performance and mass/volume requirements, while having the flexibility of working with high-density propellants, and compatibility with the onboard power source. The Inductive Coupled Electromagnetic (ICE) thruster has the potential to achieve the highest level performance in all of these criteria, making it ideal for small satellite station-keeping and de-orbit maneuvers. The plasma generation is achieved with a small (~4 cm diameter), spiral cut, porous stainless steel antenna with an integrated RF oscillator. The ICE thruster positions the coil driver, as well as all other circuit elements, immersed in the liquid propellant providing for a PPU energy transfer efficiency of near unity. The use of a porous material as the interface between the driver coil and plasma generation zone at the thruster exit eliminates the need for a complex, miniature high pressure gas feed and valve system. A number of ICE developmental milestones have been achieved. Preliminary work has characterized the influence of the coil injector porosity on the mass flow rate of liquid water into the plasma generation zone. The device has been operated on a thrust stand, and preliminary results will be discussed. Work is now underway to transform the present form of the ICE to a proto-flight thruster.

*This work was supported by a grant from NASA.

16:30

WF1 5 Flow separation control over a NACA0015 airfoil by nanosecond-pulse-driven plasma actuator ATSUSHI KOMURO, KEISUKE TAKASHIMA, *Department of Electrical Engineering, Tohoku University* NAOKI TANAKA, TAKAHIRO SENZAKI, DAIJU NUMATA, *Department of Aerospace Engineering, Tohoku University* TOSHIRO KANEKO, AKIRA ANDO, *Department of Electrical Engineering, Tohoku University* KEISUKE ASAI, *Department of Aerospace Engineering, Tohoku University* Separation flow control using a nanosecond-pulse-driven plasma actuator was studied experimentally. Wind tunnel experiments on a 10-cm chord NACA0015 airfoil were carried out at various post-stall angles of attack for free stream velocity up to 40 m/s. The pressure distribution on an airfoil surface was measured and the results showed that the nanosecond-pulse-driven plasma actuator caused flow attachment to the airfoil surface at post-stall angles. We use the custom-made pulse power source which can be operated in various operation mode such as continuous frequency mode and burst pulse mode. The effects of the pulse repetition rate, amplitude of the voltage, and rise rate of the voltage on the flow were measured. The results show that the most effective frequency of the voltage changes depending on the angle of attack and the velocity of the free stream. Additionally, the flow around the airfoil was visualized by the smoke-wire method. It is clearly shown that the normally separated flow is reattached to the suction surface of the airfoil by an on-off control of the plasma actuator.

16:45

WF1 6 Optimizations of the RailPAc Plasma Actuator for Atmospheric Aerodynamic Flow Control MILES GRAY, YOUNG-JOON CHOI, LAXMINARAYAN RAJA, JAYANT SIROHI, *University of Texas at Austin* Dielectric barrier discharge (DBD) actuators, a type of electrohydrodynamic (EHD) plasma actuator, have generated considerable interest in recent years. However, theoretical performance limitations hinder their application for high speed flows [1]. Magnetohydrodynamic (MHD) plasma actuators with higher control authority circumvent these limitations, offering an excellent alternative. The rail plasma actuator (RailPAc) is an MHD actuator which uses Lorentz force to impart momentum to the surrounding air [2]. RailPAc functions by generating a fast propagating arc column between two rail electrodes that accelerate the arc through $J \times B$ forces in a self-induced B-field. The arc column drags the surrounding air to induce aerodynamic flow motion. Our current work on the RailPAc focuses on a novel arc ignition method allowing for repeatable RailPAc firing necessary for any real world application as well as the effects of temperature, rail material, size, and external magnetic fields on induced velocities.

[1] D. F. Opaits *et al.*, J. Appl. Phys. **104**, 043304.
[2] B. Pafford *et al.*, J. Appl. Phys. D **46**, 485208.

17:00

WF1 7 Theoretical Modeling of Pulse Discharge Cycle in DBD Plasma Actuator SHINTARO SATO, NAOFUMI OHNISHI, *Tohoku University* In order to reveal a detailed mechanism of discharge cycle in dielectric barrier discharge (DBD) plasma actuator, we have conducted two-dimensional simulations of the DBD plasma actuator with a drift-diffusion model and theoretical analysis based on them. There are two distinct phases in the discharge process when a positive ramp voltage is applied to the exposed electrode. In the first phase, an ion cloud is formed at the edge of the exposed electrode due to electron avalanche. A simple theoretical model is proposed that considers time evolution of electron number density at the edge of the exposed electrode using the first Townsend ionization coefficient and provides a good agreement with the result of the numerical simulation. In the second phase, the cloud expands along the dielectric surface, followed by the streamer propagation at a high velocity. The period of streamer discharge cycle becomes shorter as the voltage slope increases. The simulation result shows that the period of the first phase is inversely proportional to the voltage slope, while that of the second phase is inversely proportional to the square of the voltage slope.

17:15

WF1 8 Piezoelectric transformers for the production of low-voltage atmospheric-pressure gas discharges and electrohydrodynamic flows MICHAEL JOHNSON, *University of Notre Dame* MARK MCDONALD, *Intel Corporation* DAVID GO, *University of Notre Dame* Typically, atmospheric-pressure gas discharges are formed by the application of very high voltages, ~ kV, to metal electrodes. However, for some applications, including hand-held devices, such voltages can be prohibitive from a design perspective. In this work, we explore using a piezoelectric transformer to amplify a relatively small voltage input (~ 10 V) to a sufficiently high potential to breakdown air. Analogous to classical magnetic transformers which convert between magnetic and electrical energy to produce a gain in voltage, piezoelectric transformers use the electromechanical coupling present within the piezoelectric to produce a similar voltage gain. As such, a high potential can be formed on the surface of a piezoelectric crystal that is sufficient to form a corona-like discharge. In this work, we demonstrate the generation of atmospheric air discharges off of the surface of piezoelectric transformers with input voltages as low as 7 Vamp. We use two different configurations, one with the piezoelectric surface acting as an electrode in a traditional two-electrode corona discharge configuration and the second using no second electrode to form a surface discharge. One potential application of these piezoelectric-driven discharges is as electrohydrodynamic flow sources, also called ionic wind generators. Using a combination of infrared thermography and anemometry, we measure the induced flows by piezoelectric-driven discharges, and explore how the external system and resonant frequency affect flow generation.

SESSION WF2: MAGNETRON SPUTTER DEPOSITION
Friday Afternoon, 16 October 2015; Room: 308 AB at 15:30; Yuichi Setsuhara, Osaka University, presiding

Invited Papers

15:30
WF2 1 Self-Assembled Multi-Layer a-C:H/Me Coatings by Reactive Sputter Deposition
JYH-MING TING, *Department of Materials Science and Engineering, National Cheng Kung University, Taiwan*

The growth and characteristics of metal containing amorphous hydrogenated carbon thin films (a-C:H/Me) were studied in this research. The formation of self-assembled, alternating nano-layered structures are addressed. a-C:H/Me thin films were synthesized using one single target, a rotating but not revolving substrate, and constant feed gas compositions in a conventional reactive sputter deposition chamber. The metals used include Al, Si, Cu, Pt, Fe and Ni. Various mixtures of methane and argon having fixed total flow rates were used as the feed stocks. A number of growth parameters, including methane concentration, working pressure, electrode distance, dc power, substrate bias, and substrate temperature were used. The resulting a-C:H/Me thin films were found to exhibit three different structures. Among them, self-assembled, alternating nano-layered structures were observed in a-C:H/Cu, a-C:H/Pt, a-C:H/Fe, and a-C:H/Ni thin films. It was found that such self-assembled, alternating nano-layered structures can be obtained under controlled growth parameters for selected metals. A growth mechanism based on the considerations of clustering of carbon and metal, segregation of carbon, catalytic effects of metal, formation of carbide, energy of adatoms, and surface diffusion of metal and carbon, has been developed. Further data analysis was also performed to verify the validity of the mechanism.

Contributed Papers

16:00
WF2 2 Applying Composition Control to Enhance the Mechanical and Thermal Properties of Zr-Cu-Ni-Al-N Thin Film Metallic Glass JOSEPH LEE, JENQ-GONG DUH, *National Tsing-Hua University* This study focuses on the correlations among the compositions of Zr-Cu-Ni-Al-N thin film metallic glass (TFMG) and their properties. The TFMG was prepared by DC magnetron co-sputtering technique with Zr-Cu and Ni-Al targets. By adjusting working power, pressure and nitrogen flow rate, thin films with various constituents were fabricated. Also, the effect of Zr/Cu ratio on the physical properties will be explored. With the increasing nitrogen content in the system, the hardness was improved up to 100% as compared to Zr-Cu TFMG. The strengthening mainly results from the atomic radii difference, and the enthalpy of mixing among mutual atomic bonding. In pursuit of high hardness, whether the coating still belongs to a metallic glass is critical. Differential scanning calorimetry (DSC) analysis further identifies the metallic glass characteristics of films with the formation of super-cooling regions. Finally, a Zr-Cu-Ni-Al-N TFMG with appropriate composition to exhibit improved hardness, thermal stability, and antimicrobial ability was revealed and discussed.

16:15
WF2 3 Fabrication of spin valve junctions based on $Fe/Fe_3Si/FeSi_2/Fe_3Si$ quadrilayered films by facing targets direct-current sputtering* KAZUYA ISHIBASHI, KAZUTOSHI NAKASHIMA, *Department of Applied Science for Electronics and Materials, Kyushu University* KEN-ICHIRO SAKAI, *Department of Control and Information Systems Engineering, Kurume National College of Technology* TSUYOSHI YOSHITAKE, *Department of Applied Science for Electronics and Materials, Kyushu University* In order to prepare magnetic multilayered films applicable to spin devices, the film preparation method is an important key that determines the quality of the spin devices, such as interfaces between layers and crystalline orientations. A facing targets direct-current sputtering (FTDCS) method, in which a couple of targets are positioned in parallel and a substrate is set in the direction perpendicular to the two targets, has the following features: (i) less plasma damage, (ii) fewer rises in the substrate temperature, and (iii) small stoichiometric differences between the target and film, owing to a substrate is free of the plasma. These features should be beneficial to $Fe_3Si/FeSi_2$ multilayered films at low substrate temperatures, with Fe_3Si and $FeSi_2$ sintered targets. In this study, $Fe/Fe_3Si/FeSi_2/Fe_3Si$ multilayered films were prepared by employing the FTDCS method. The bottom Fe_3Si layers were epitaxially grown on Si(111) substrates, and they exhibited small coercive forces of less than 10 Oe. Posterior to $FeSi_2$ layers being deposited on the bottom Fe_3Si layers, polycrystalline Fe_3Si and Fe were successively deposited on the $FeSi_2$ layers. The resultant multilayered films showed sharp signals due to magnetoresistance as spin valves.

*This work was supported by JSPS KAKENHI Grant Number 15K21594.

16:30
WF2 4 Surface Roughness Control of DC Sputter Film Deposition by Superposition of VHF Power FUKUI TAKASHI, SUYAMA TAKU, FUKUOKA YUSHI, SASAI KENSUKE, *Nagoya University* TOYODA HIROTAKA, *Nagoya University, PLANT, Nagoya University* Magnetron plasmas are one of the most important tools for sputter deposition of thin films. However, energetic particles from the sputtered target such as backscattered rare gas atoms or oxygen negative ions (O^-) from oxide targets sometimes induce physical and chemical damages as well as surface roughening to the deposited film surface during the sputtering processes. In our previous work, we have investigated spatial and

energy distributions of O^- ion in a RF plasma. We also have shown suppression of O^- energy with VHF-superimposition and that O^- energy can be controlled by a parameter R, which is a ratio of the VHF power to the total input power (VHF power + DC power). In this study, influence of the VHF superposition on the deposition properties of ITO films such as deposition rate, RMS roughness or electrical resistivity is investigated. Deposition rate is strongly influenced by the VHF superposition although the DC current is the same, suggesting variation of sputter yield and positive ion current due to lowering of the target voltage. By superposition of the VHF power up to $R \sim 90\%$, improved RMS roughness and the electrical resistivity is observed.

16:45

WF2 5 Study of the mechanical properties and the microstructure of magnetron sputtered MoBC coatings* VILMA BURSIKOVA, PAVEL SOUCEK, PETR VASINA, LUKAS ZABRANSKY, *Department of Physical Electronics, Faculty of Science, Masaryk University* JIRI BURSIK, *Institute of Physics of Materials, Academy of Sciences of the Czech Republic* The aim of the present work was to prepare Mo_2BC films using magnetron sputtering. The studied films were deposited using a sputtering device equipped by four confocally arranged magnetrons accommodating 3 inch sputtering targets. All magnetron heads were aimed at a rotatable and biasable substrate holder that can be heated up to 750° C. Molybdenum, carbon and B_4C targets were co-sputtered simultaneously. Mo and B_4C targets were DC powered, while carbon target was connected to pulsed DC generator capable of pulsing up to frequency of 350 kHz. The pulsing frequency, bias and substrate temperatures were varied. The mechanical properties of layers were characterized by means of nanoindentation experiments using a Hysitron dual head TI950 triboindenter in both static and dynamic loading regime. The results of mechanical testing and XRD studies were correlated with microstructure observations by means of electron microscopy using a Tescan LYRA 3XMU SEM × FIB scanning electron microscope (SEM), a Philips CM12 STEM transmission electron microscope (TEM) and a JEOL 2010F high resolution TEM. Thin lamellar cross sections for TEM observations were prepared using a focused ion beam (FIB) in SEM.

*The research was supported by Czech Science Foundation (project 15-17875S), by European Regional Development Fund (project CZ.1.05/2.1.00/03.0086) and by Ministry of Education Youth and Sports of Czech Republic (project LO1411 (NPU I)).

17:00

WF2 6 Scalable Plasma Engineering For Transparent-Conductive Performance Improvment in Al-Doped ZnO Thin Films MANISH KUMAR, LONG WEN, JEON HAN, *Sungkyunkwan University* CENTER FOR ADVANCE PLASMA SURFACE TECHNOLOGY TEAM ZnO has been widely investigated for applications in opto-and nanoelectronics; such as automobile devices (e.g. panel lighting), traffic lights, optical recording media, scanning readers, video game consoles and LEDs. When it is doped, the special characteristics of ZnO-based compounds allow them to be used as a transparent conductor. Here, we present a scalable plasma engineering process based on DC magnetron sputtering for improving the transparent conductive- characterestics in Al doped ZnO thin films. Using a highly confined magnetron system, plasma densities and electron temprature were engineered systematically and its effect on transparent-conductive characeristics of films has been studied using plasma diagnostic tools (using Langmuir probe, optical essision spectraoscopy, current density) and films characterizations. Here, using DC power in similar range of conventional DC magnetron sputtering, present process produces plasma density one order greater and remarkably higher electron temperature. Such plasma conditions lead to good crystalline films with adequate oxygen vacancies, which in turn leads highly repitible resistivities in order of 10-4 Ω cm with average transmittance more than 85% in entire visible region in 200 nm thick films.

SESSION WF3: DIELECTIC BARRIER DISCHARGES

Friday Afternoon, 16 October 2015; Room: 305 AB at 15:30; Anne Bourdon, Ecole Polytechnique, presiding

Invited Papers

15:30

WF3 1 Controlling the Porosity in Silica-like Moisture Barriers Processed in a High Current Dielectric Barrier Discharge

HINDRIK DE VRIES, *DIFFER*

The high current dielectric barrier discharge was operated in the bi-axial cylindrical electrode geometry. Silica-like films were deposited as a function of the dynamic deposition rate and subsequently characterized by ATR-FTIR and moisture permeation analysis. The relation between microstructure and permeation behaviour with deposition rate is tentatively explained by the presence of an interconnected nano-porous structure facilitating the moisture transport through the films. To overcome the moisture barrier limitations a bi-layer architecture was developed. It was shown that dense silica thin films grown on a porous silica layer can yield excellent effective moisture barrier values less than $\sim 1 \times 10^{-3}$ g/m^2 day. In collaboration with Sergey Starostin, FOM institute DIFFER.

16:00

WF3 2 Surface functionalization with atmospheric pressure DBD

FRANCESCO FRACASSI, *Dipartimento di Chimica Università di Bari - NANOTEC CNR*

Intense research efforts have been recently made to develop a large variety of deposition processes for the direct and remote DBD deposition of thin films from monomers in gas, vapor and aerosol form. In this contribution, the preparation of organic-inorganic nanocomposite coatings by DBD fed with helium and the aerosol of a dispersion of ZnO nanoparticles in hydrocarbon solvent will be described. The nanocomposite coatings show multifunctional behavior and specifically combine the photocatalytic properties of ZnO with superhydrophobicity. The DBD jet co-deposition of acrylic acid and ethylene to obtain stable coatings containing carboxylic functionalities will be also presented. Results from X-ray photoelectron spectroscopy (XPS) in conjunction with chemical derivatization, and scanning electron microscopy demonstrate the chemical and morphological stability of these coatings upon immersion in water. Finally our recent work on the plasma-enhanced chemical vapor deposition of fluoropolymers on complex three-dimensional (3D) porous substrates, such as polyurethane foams, will be shown. During the deposition, the DBD is ignited inside the porous 3D network of the foams and allows obtaining a uniform coating within their interior.

Contributed Papers

16:30

WF3 3 Modeling of a packed bed dielectric barrier discharge plasma reactor KOEN VAN LAER, *None* ANNEMIE BOGAERTS, *Prof. Dr.* The dielectric barrier discharge (DBD), as a source of non-thermal plasma, has been of interest for environmental applications for quite some time. Indeed, plasma can be an interesting alternative for conventional thermal methods, because the input energy solely goes to heating up the electrons, while the rest of the plasma particles (i.e. radicals, ions, neutrals) stay at room temperature. However, the feasible energy efficiency appeared to be on the low side. In order to overcome this, a dielectric packing was introduced in the gas gap of the reactor, forming a so-called packed bed plasma reactor (PBPR). Using COMSOL's built-in plasma module, two different complementary 2D axisymmetric fluid models are used to study the intrinsic 3D problem. As a first step, helium is used as discharge gas, at atmospheric pressure and room temperature. It was found that the contact points between the packing beads are of direct importance to initiate the plasma. Indeed, at low applied potential, the discharge is initiated directly at the contact points and stays in this region. However, when a high enough potential is applied, the plasma will be able to travel through the gaps in between the beads, spreading from one wall to the other.

16:45

WF3 4 Self organization in dielectric barrier discharge and control of hexagonal structures* SEIJI MUKAIGAWA, TAKUYA KAMEYAMA, TOMOHIRO KUDOH, ATSUYA YOKOTA, KOSUKE JUMONJI, KOICHI TAKAKI, *Iwate University* Symmetric self organized discharge filaments have been observed in the 140 μm microgap dielectric barrier discharge between two parallel glass plates. The spatial distribution of these discharge filaments were revealed by a discharge experiment in which the thickness of dielectric barrier and pressure were changed. An image of the discharge in nano seconds was obtained using an intensified charge-coupled device (ICCD) camera. The diameters of the self-organized filaments, and the distance between them were obtained using the ICCD images. We found that if the dielectric barrier is thinner then the lattice spacing (the distance between the filaments) are smaller. In addition, the lattice spacing at 760 Torr was smaller than that at 380 torr. Numerical calculation showed the same tendency for lattice spacing as the hexagonal pattern structures in the discharge experiments. Therefore, the lattice spacing of hexagonal patterns can be controlled by manipulating the control parameters in an experiment.

*This work was supported by JSPS KAKENHI Grant Numbers 26390094, 24540530.

17:00

WF3 5 Surface dielectric barrier discharges generated in CO_2 exhibiting field emission at high pressure* DAVID PAI, *Institut PPRIME* SVEN STAUSS, KAZUO TERASHIMA, *University of Tokyo* For dielectric barrier discharges (DBDs) generated at atmospheric pressure or less, field emission has generally not been considered as a possible mechanism of electron emission. At higher pressures, however, gas-phase ionization may only become significant at electric fields that are comparable to the threshold field for field emission. Surface DBDs are studied experimentally in CO_2 from atmospheric pressure up to supercritical conditions (T_c = 304.13 K, p_c = 7.4 MPa). Two discharge regimes are generated using 10-kHz AC excitation. The "standard" regime is similar to previously studied surface DBDs in terms of onset voltage as a function of pressure, as well as electrical and optical emission characteristics. However, a "field-emitting" regime emerges starting from 0.7 MPa that exhibits constant onset voltage up to 7.9 MPa, purely continuum emission spectra in the visible/near-infrared range, and current waveforms similar to an atmospheric-pressure Townsend discharge. The maximum amount of negative charge deposited as a function of the applied voltage amplitude is consistent with the Fowler-Nordheim equation, demonstrating the presence of field emission. This behavior cannot be attributed to the Townsend or streamer ionization mechanisms, secondary electron emission, or non-discharge processes. No field-emitting structures are specially added to the electrodes. The onset voltage of the field-emitting regime does not follow the modified Paschen's law for field emission-assisted breakdown.

*This work was supported financially in part by MEXT and JSPS.

17:15

WF3 6 The influence of reactor walls surface conductivity on carbon dioxide discharge properties in DBD IGOR BELOV, SABINE PAULUSSEN, *VITO, Sustainable Materials Management, Mol, Belgium* ANNEMIE BOGAERTS, *University of Antwerp, PLASMANT, Antwerp, Belgium* This work examines the properties of a dielectric barrier discharge (DBD) reactor, build for CO_2 decomposition, by means of electrical characterization, optical emission spectroscopy and gas chromatography. Several features of electric waveforms specific for CO_2 discharges in the DBD systems were observed (asymmetry, high-current sparse peaks). Current waveforms revealed the difference in the microdischarge development of the positive and the negative half-cycles of the applied voltage. It was found that the discharge current is highly promoted in configurations (i.e. in certain half-cycles) with a conductive cathode. The transition from an asymmetric current waveform to a symmetric one was investigated during tests on CO_2 decomposition and subsequent conductive carbon film deposition on the reactor walls. The double dielectric (DD) and metal-dielectric (MD) configurations were compared in terms of discharge properties and conversion efficiency. The same effect of discharge current enhancement was observed when a conductive film was deposited on the outer dielectric in the DD configuration. Consequently, also conversion efficiency was found to increase. In addition, optical emission spectroscopy confirmed the strong correlation of plasma reactivity with the presence of a conductive coating on one of the electrodes. This way it is possible to control the process efficiency and modify the microdischarge activity in the DD reactor without using elaborated dielectric materials.

SESSION WF4: BIOMEDICAL APPLICATIONS

Friday Afternoon, 16 October 2015; Room: 303 AB at 15:30; Deborah O'Connell, University of York, presiding

Invited Papers

15:30

WF4 1 Plasma Polymers for Biomedical Applications

FARZANEH AREFI, *Sorbonne Universités, UPMC Univ Paris 06 and CNRS, UMR8235, LISE, 4 place Jussieu, 75252 Paris, France*

There exists an abundant literature on polymers used for biomedical applications. However, the research described in the present talk deals with the plasma (co-) polymerization of different organic precursors for surface modifications of a variety of substrates in order to tailor the surface physico-chemical properties for tuneable biomolecule-surface interactions required for a wide range of biomedical applications such as antifouling properties, controlled drug delivery systems (DDS), cell-surface interactions for tissue engineering applications, etc. A low pressure inductively excited plasma, and a custom made open air DBD APPJ have been used for the plasma (co-) polymerization. Furthermore with the help of a coaxial double tube configuration of APPJ, one can minimize the influence of the entrainment of air in an open-air system in order to avoid enhanced plasma fragmentation and loss of the retention of the functional groups of the precursors, which is usually required for biomedical applications. The stability to washing with water and PBS of the deposited organic plasma polymers obtained with the APPJ at two different frequencies i.e. at 18 kHz and at 13.56 MHz will be compared. Examples such as multilayered DDS obtained from the plasma copolymerization of PCL-PEG coatings on collagen for controlled release of carboplatin for anticancer therapies and *in-vitro* experiments will be presented. In the near future, DDS loaded with carboplatin will be tested *in-vivo* on mice infected with mouse colon cancer CT26 and ovarian cancer cells OVCAR-3. Another example presented in the talk will be the deposition of biocompatible biodegradable PEG-PCL copolymers on Calcium Phosphates (CaPs) scaffolds, which are suitable biomaterial for bone regeneration materials, in order to control the kinetics of drug release.

16:00

WF4 2 Diagnostics of Nonthermal Atmospheric Pressure Plasma for Plasma Biosciences and their Biological Cell Interactions throughout Ultraviolet Photolysis*

EUN HA CHOI, *Kwangwoon University*

Nonthermal biocompatible plasma (bioplasma) sources and their characteristics operating at atmospheric pressure have been introduced for biological cell interactions, especially used in Plasma Bioscience Research Center (PBRC), Korea. The electron temperatures and plasma densities are measured and analysed here for the nonthermal bioplasma sources in PBRC. Herein, we introduced plasma-initiated ultraviolet photolysis of water inside the biological solutions, to generate the reactive hydroxyl radical OH and hydrogen peroxide H_2O_2 species that may results in apoptotic cell death. These molecular changes in genomic DNA have been investigated by the confocal Raman and circular dichroism spectroscopy. We also found enhanced anticancer effect of monocytes and macrophages activated by nonthermal plasma which act as immune-modulator on these immune cells. Further, we investigated the action of the microsecond pulsed plasma activated media (MPP-AM) action on the lung cancer cells and its DNA oxidation pathway. Moreover, we also checked the action of heavy water and normal water activated water on the different cancer cell lines, to show the apoptotic cell death. In collaboration with Young Joon Hong, Pankaj Attri, Naresh Kumar, and Nagendra Kaushik, Kwangwoon University.

*This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIP) (No. 2010-0027963).

Contributed Papers

16:30

WF4 3 Monolithic Structure of Integrated Coaxial Micro-hollow Dielectric Barrier Discharges: Characterization for Environmental and Biomedical Application KUNIHIDE TACHIBANA, *Osaka Electro-Communication University* HIDEKI MOTOMURA, *Ehime University* Dielectric barrier discharge (DBD) devices operated at atmospheric pressure are of great uses for varieties of environmental and biomedical applications. Instead of commonly used parallel plate structures we have ever developed an alternative structure of integrated coaxial micro-hollow discharges by stacking two ceramic insulated metal meshes, which can be scaled to any size keeping uniform discharge. Since its new version of monolithic structure became available, we tried in this work to characterize the properties of discharge and production of OH radicals with several gas species using optical emission and laser induced fluorescence (LIF) spectroscopy techniques. Spatiotemporal behavior of DBD showed ring structures at larger hole-diameters than 1 mm but changed to convex structures at 0.6 mm hole-diameter. Large amounts of OH radicals were produced with He and Ar gases but almost none with N_2 gas. Spatial distribution of OH radicals diagnosed by LIF showed the propagation with the gas flow. Rotational temperature estimated from OH (0-0) band was larger than those from N_2^+ (0-0) and (0-1) bands.

16:45

WF4 4 Localized Gene Transfection through Cell Membrane Stimulated by Micro Solution Plasma* TOSHIRO KANEKO, YUTARO HOKARI, SHOTA SASAKI, *Department of Electronic*

Engineering, Tohoku University MAKOTO KANZAKI, *Department of Biomedical Engineering, Tohoku University* TAKEHIKO SATO, *Institute of Fluid Science, Tohoku University* The micro-scale plasmas generated in solution (micro solution plasmas) are strongly desired to realize in vivo gene transfection, because most of the human body consists of water and internal organs are filled with solution. We attempt to generate the micro solution plasma and apply it to the living cells for clarifying the transfection mechanism toward developing minimally-invasive localized gene transfection. In this experiment, the coaxial type electrode is used to make the micro-scale plasma, where the curvature radius of the high voltage electrode is less than 1 μm. By applying a pulse voltage to the electrode, we succeed in generating the micro-scale plasma in phosphate buffered saline (PBS), which could stimulate the adherent cells in PBS. After the micro solution plasma irradiation, the cell membrane permeability is evaluated using fluorescent probe YOYO-1 [1,2]. The YOYO-1 fluorescence is strongly observed only in the localized plasma irradiation area which can be controlled by the pulse width. Based on this result, the cell membrane permeability is found to be locally enhanced by the stimulation of the irradiated micro solution plasma.

*This work was supported by JSPS KAKENHI Grant No. 24108004 and the Knowledge based Medical Device Cluster/Miyagi Area.

[1]S. Sasaki *et al.*, Appl. Phys. Exp. **7**, 026202 (2014).

[2]T. Kaneko *et al.*, Biointerphases **10**, 029531 (2015).

17:00

WF4 5 Acquisition of Cell-Adhesion Ability on the Surface of Crosslinked Albumin Films Irradiated with Atmospheric-Pressure Plasma Jets MAMI IWAMURA, KOTA NAKAJIMA, RYOSUKE TAGA, KENJI TANAKA, TATSURU SHIRAFUJI, AKIRA TACHIBANA, TOSHIZUMI TANABE, *Osaka City University* We have applied an atmospheric-pressure plasma jet (APPJ) using He gas to surface treatment on crosslinked albumin films. The crosslinked albumin films, to which L929 cells do not attach, acquire the L929 cell-adhesion ability by the APPJ irradiation in a quite short time of 300 s. The processing speed by the APPJ is 40-fold faster than a conventional ultraviolet light irradiation process. Furthermore, the elongated spindle-like morphology of the cells indicates strong adhesion between the cells and the film. We have confirmed the formation of hydrophilic chemical bonds such as COH and COOH through X-ray photoelectron spectroscopy (XPS) on the APPJ-irradiated crosslinked albumin films. An increase in the cell-adhesion ability with increasing the APPJ irradiation time has a positive correlation with the increase in O (1s) peak intensity in the XPS spectra of the films. However, the optical emission spectrum of the APPJ does not show strong emission of O (777 nm) and OH (309 nm). These results suggest that the causes of the hydrophilic chemical bonds are the dangling bond formation by abundant excited N_2 and He, and successive oxidation of the dangling bonds by ambient air and/or water vapor.

17:15

WF4 6 Measurement of the diffusion coefficient of supported lipid bilayer irradiated with dielectric barrier discharge YOSHIYUKI SUDA, RYUMA YAMASHITA, KOTA YUSA, TORU HARIGAI, HIROFUMI TAKIKAWA, *Toyohashi University of Technology* AKINORI ODA, *Chiba Institute of Technology* RYUGO TERO, *Toyohashi University of Technology* We have focused on the behavior of artificial cell membrane system at solid-liquid interface. We irradiated the Ar or He gas dielectric barrier discharge (DBD) onto a supported lipid bilayer (SLB) [1,2]. Observation with a fluorescence microscope and atomic force microscope revealed the formation of pores on the order of 10 nm–1 μm in size without a change in pH. We propose that SLBs are effective for obtaining information about the physical and chemical modification of cell membranes induced by plasma. SLB was produced in buffer solution on the SiO_2 / Si substrate using the vesicle fusion method. DOPC (dioleoylphosphatidylcholine) and Rb-DOPE (rhodamine B-dioleoylphosphatidylethanolamine) were used as a lipid and fluorescent dye-labeled lipid, respectively. The diffusion coefficients of the SLBs before and after the He gas DBD irradiation were measured using a confocal laser scanning microscopy. It was found that the diffusion coefficient became 30% lower after the DBD irradiation.

[1]Ryugo Tero, Yoshiyuki Suda, Ryo Kato, Hideto Tanoue, and Hirofumi Takikawa, Appl. Phys. Exp. **7**, 077001 (2014).

[2]Yoshiyuki Suda, Akinori Oda, Ryo Kato, Ryuma Yamashita, Hideto Tanoue, Hirofumi Takikawa, and Ryugo Tero, Jpn. J. Appl. Phys. **54**, 01AF03 (2015).

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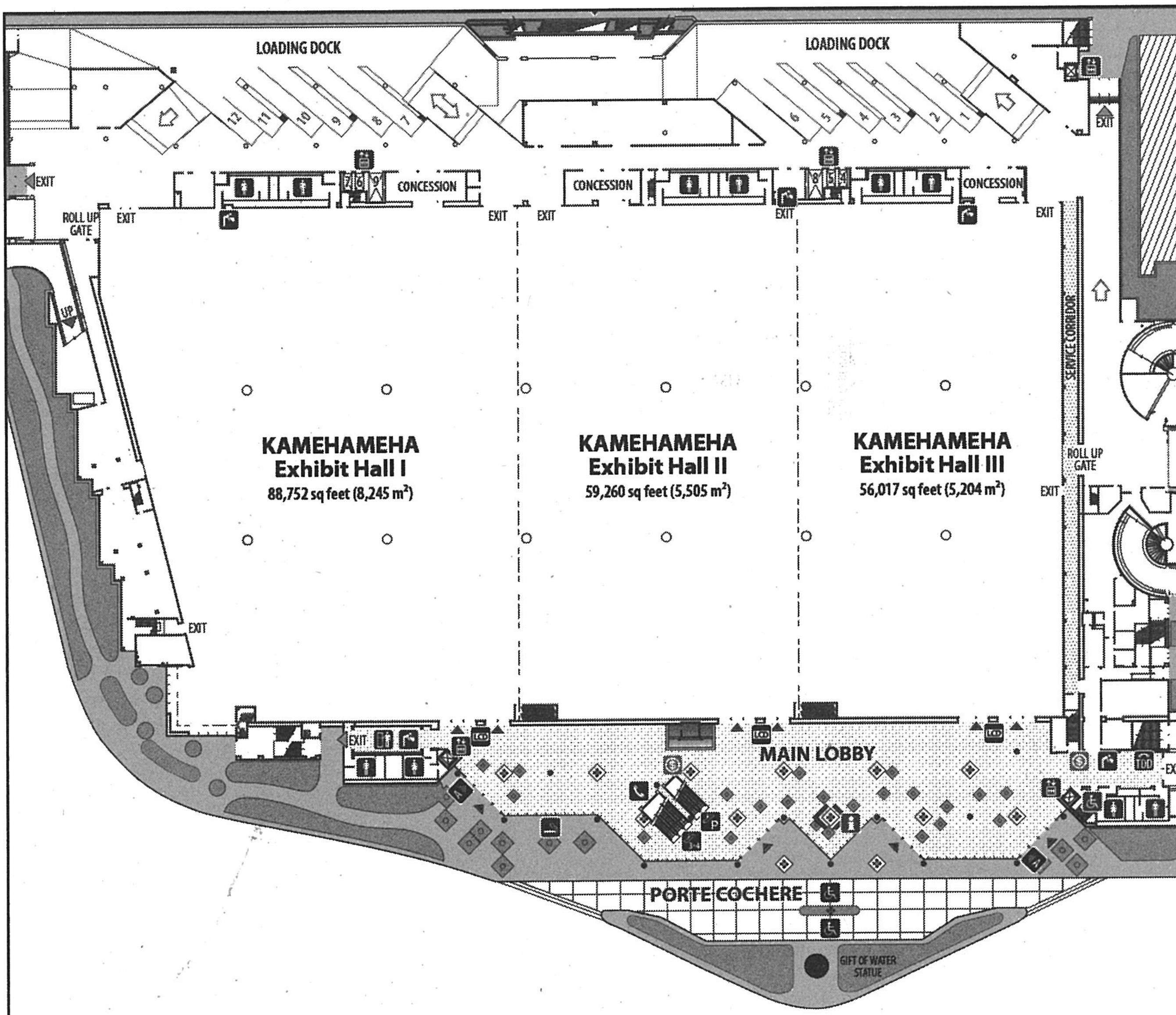
NOTES

HAWAII CONVENTION CENTER

LEVEL 1 | Exhibit Hall/Lobby



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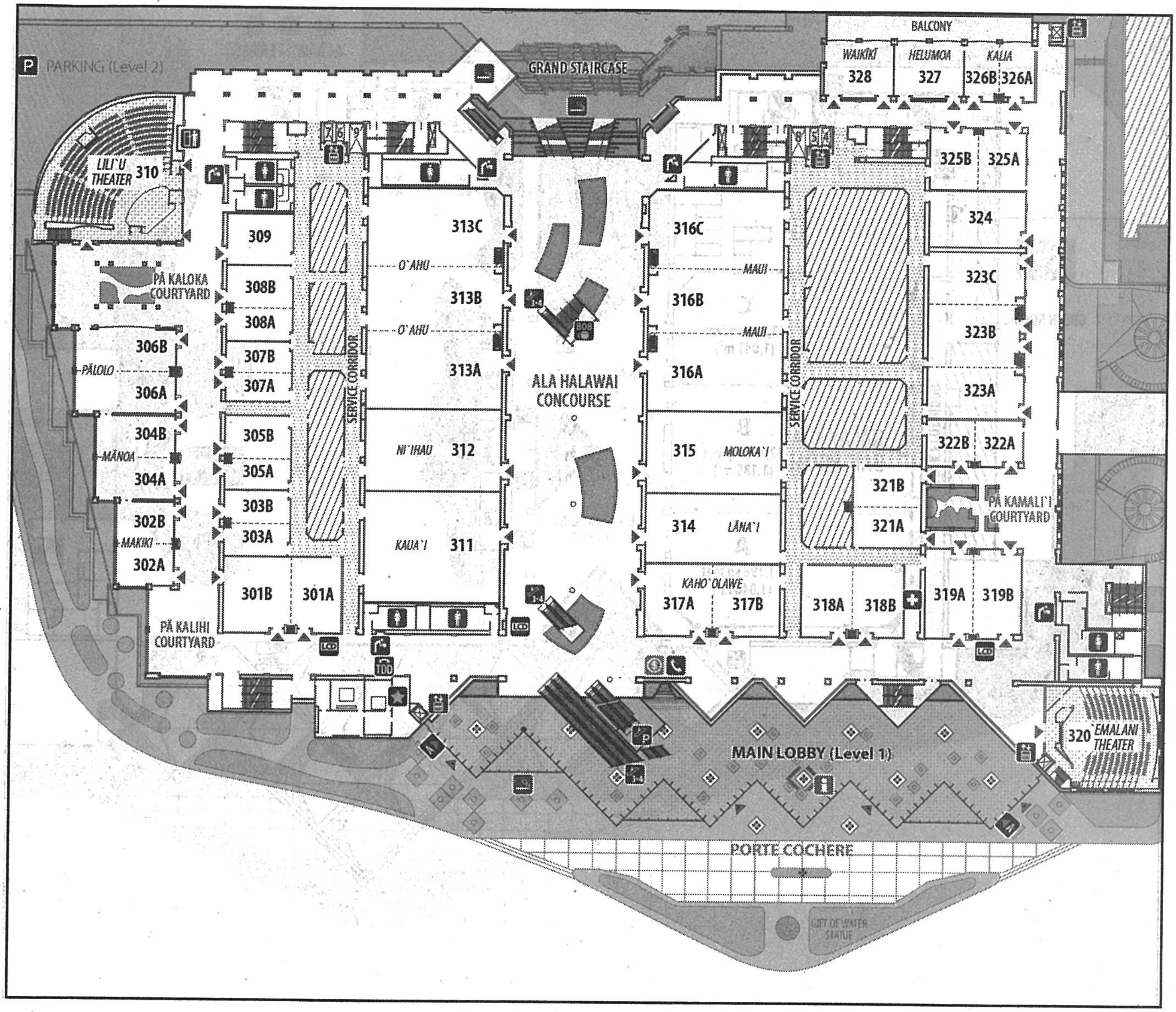
LEVEL 3 | Meeting Rooms/Theaters



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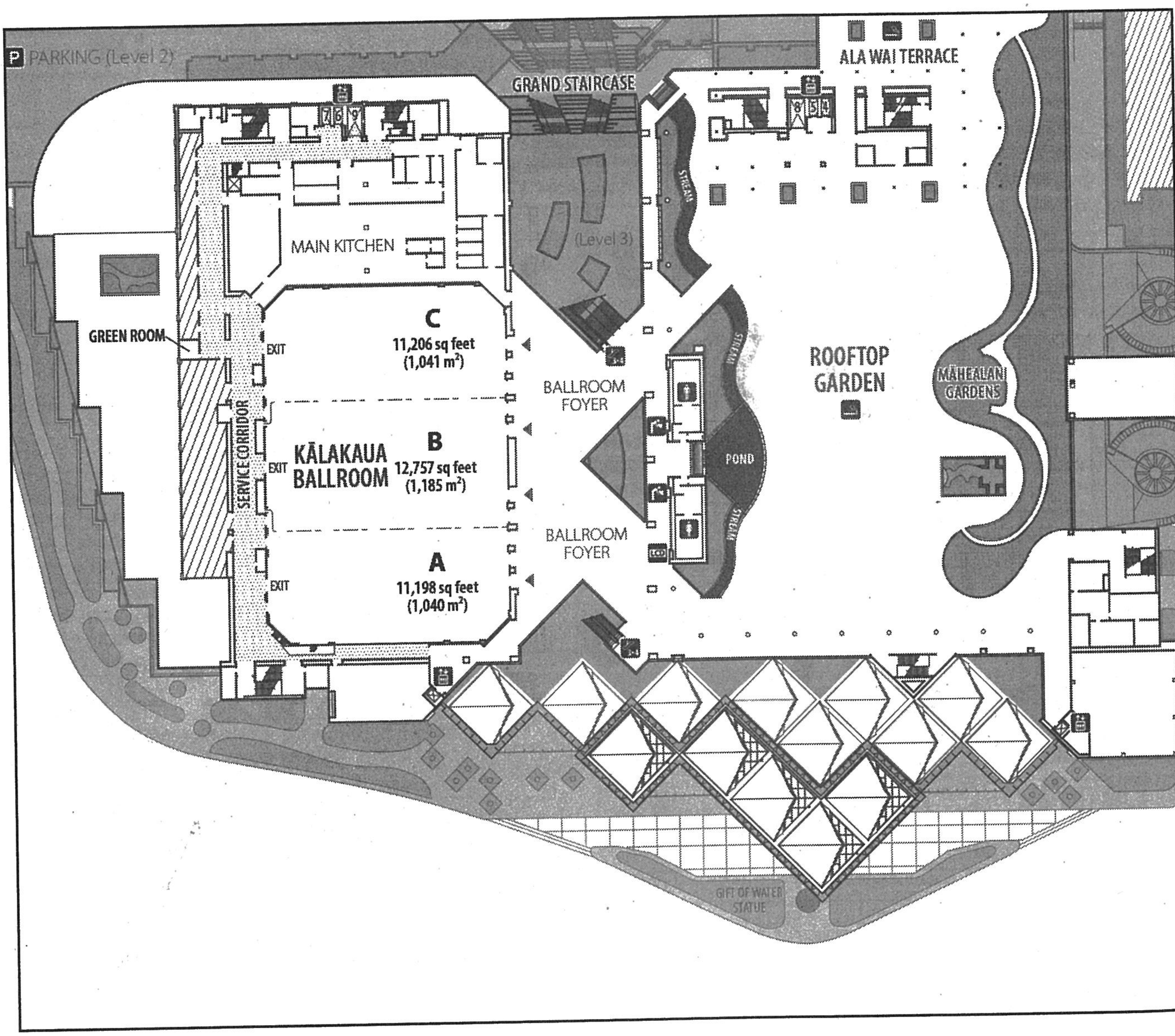
LEVEL 4 | Ballroom/Rooftop Garden



Epitome of the 2015 Annual Fall Meeting of the Gaseous Electronics Conference

13:00 MONDAY AFTERNOON
12 OCTOBER 2015

AM1 **Challenge of Plasma Science towards Future Medicine Workshop I**
Shinya Toyokuni, Klaus-Dieter Weltmann, Alexander Fridman, Eun Ha Choi
Room: 301 B

15:30 MONDAY AFTERNOON
12 OCTOBER 2015

BM1 **Challenge of Plasma Science towards Future Medicine Workshop II**
Nobuyuki Shimizu, Eric Robert, David Graves
Room: 301 B

18:00 MONDAY EVENING
12 OCTOBER 2015

CM2 **Opening Reception**
Room: 311

08:00 TUESDAY MORNING
13 OCTOBER 2015

DT1 **Plasma Thrusters**
Room: 301 B

DT2 **Plasma Surface Interactions I**
Osamu Sakai
Room: 308 AB

DT3 **Optical Diagnostics I**
Natalia MacDonald-Tenenbaum
Room: 305 AB

DT4 **Basic Low Pressure Plasma Physics**
Room: 303 AB

10:00 TUESDAY MORNING
13 OCTOBER 2015

ET1 **Reactive Species for Plasma Medicine**
Deborah O'Connell, Ryo Ono
Room: 301 B

ET2 **Capacitively Coupled Plasmas I**
Erik Johnson
Room: 308 AB

ET3 **Diagnostic Probes**
David Gahan
Room: 305 AB

ET4 **Positron and Electron Collisions**
C.M. Surko, James Sullivan
Room: 303 AB

13:30 TUESDAY AFTERNOON
13 OCTOBER 2015

FT1 **Plasma Medicine**
Thomas von Woedtke
Room: 301 B

FT2 **Inductively Coupled Plasmas**
Room: 308 AB

FT3 **Microplasmas**
Mikhail Benilov
Room: 305 AB

FT4 **Thermal Plasmas; Materials Applications**
Jochen Schein
Room: 303 AB

16:00 TUESDAY AFTERNOON
13 OCTOBER 2015

GT1 **Poster Session I (4:00pm - 6:00 pm)**
Room: Exhibit Hall III

20:00 TUESDAY EVENING
13 OCTOBER 2015

HT1 **Atomic and Molecular Scattering Data for Plasma and Related Applications Workshop I**
Igor Bray, Oleg Zatsarinny, Mark J. Kushner, Hiroshi Tanaka
Room: 301 B

08:00 WEDNESDAY MORNING
14 OCTOBER 2015

IW1 **Disinfection/Sterlization by Plasma**
Masaaki Nagatsu
Room: 301 B

IW2 **Ion Assisted Deposition**
Room: 308 AB

IW3 **Modeling and Simulation I**
Keith Cartwright, Andrew Christlieb
Room: 305 AB

IW4 **Electron and Photon Collisions**
Joan Dreiling, Bruno deHarak
Room: 303 AB

10:00 WEDNESDAY MORNING
14 OCTOBER 2015

JW1 **GEC & ICRP Plenary Sessions, Business Meeting**
Kouichi Ono, Timothy Gay
Room: 311

13:30 WEDNESDAY AFTERNOON
14 OCTOBER 2015

KW1 **Plasma Gas Conversion**
Gerard van Rooij
Room: 301 B

KW2 **Magnetically Enhanced Plasmas**
Hirotake Sugawara
Room: 308 AB

KW3 **Modeling and Simulation II**
Jan Trieschmann
Room: 305 AB

KW4 **Atmospheric & Thermal Plasmas**
Masaya Shigeta, Peter Bruggeman
Room: 303 AB

16:00 WEDNESDAY AFTERNOON
14 OCTOBER 2015

LW1 **Poster Session II (4:00pm - 6:00pm)**
Room: Exhibit Hall III

20:00 WEDNESDAY EVENING
14 OCTOBER 2015

MW1 **Atomic and Molecular Scattering Data for Plasma and Related Applications Workshop II**
Yuri Ralchenko, Hajime Tanuma, Predrag Krstic
Room: 301 B

08:00 THURSDAY MORNING
15 OCTOBER 2015

NR1 **Plasma Sources for Biomedical Applications I**
Volker Schulz-von der Gathen, Stephan Reuter
Room: 301 B

NR2 **Plasma CVD/Radical Assisted CVD**
Room: 308 AB

NR3 **Plasma Sheaths and Boundary Layers**
John Caughman
Room: 305 AB

NR4 **Plasma-Assisted Combustion**
Room: 303 AB

10:00 THURSDAY MORNING
15 OCTOBER 2015

OR1 **Plasma Interaction with Liquids I**
Room: 301 B

OR2 **Plasma Etching I**
Demetre Economou, Nobuyuki Kuboi
Room: 308 AB

OR3 **Atmospheric Discharges: Pulses and Streamers**
Anne Bourdon, Kentaro Tomita
Room: 305 AB

OR4 **Electron-Impact Ionization**
Masahiko Takahashi, Don Madison
Room: 303 AB

13:30 THURSDAY AFTERNOON
15 OCTOBER 2015

PR1 **Atmospheric Plasmas I**
Timo Gans
Room: 301 B

PR2 **Capacitively Coupled Plasmas II**
Room: 308 AB

PR3 **Gas Phase Plasma Chemistry**
Room: 305 AB

PR4 **Electron Collisions**
Michael Fogle, Marco Lima
Room: 303 AB

15:30 THURSDAY AFTERNOON
15 OCTOBER 2015

QR1 **Plasma Interaction with Liquids II**
David Go, Yongfeng Li
Room: 301 B

QR2 **Plasmas for Nanotechnologies**
Holger Kersten
Room: 308 AB

QR3 **Negative Ion and Dust Particle Containing Plasmas**
Room: 305 AB

QR4 **Modeling and Simulation III**
Luis Chacon
Room: 303 AB

08:00 FRIDAY MORNING
16 OCTOBER 2015

SF1 **Atmospheric Plasmas II**
Room: 301 B

SF2 **Carbon Related Materials Deposition**
Room: 308 AB

SF3 **Optical Diagnostics II**
Ximing Zhu
Room: 305 AB

SF4 **Plasma Surface Interactions II**
Room: 303 AB

10:00 FRIDAY MORNING
16 OCTOBER 2015

TF1 **Plasma Interaction with Liquids III**
Room: 301 B

TF2 **Plasma Etching II**
Deirdre Olynick
Room: 308 AB

TF3 **Applications of Plasmas**
Sylvain Coulombe
Room: 305 AB

TF4 **Atmospheric Pressure Plasma Jets**
Laxminarayan L. Raja
Room: 303 AB

13:30 FRIDAY AFTERNOON
16 OCTOBER 2015

UF1 **Plasma Sources for Biomedical Applications II**
Vittorio Colombo, Koichi Takaki
Room: 301 B

UF2 **Diffuse Discharges**
David Smith
Room: 308 AB

UF3 **Nonequilibrium Kinetics of Low-Temperature Plasmas**
Room: 305 AB

UF4 **Heavy-Particle Collisions and Swarms**
Thomas Schlathoelter, Tom Kirchner
Room: 303 AB

15:30 FRIDAY AFTERNOON
16 OCTOBER 2015

WF1 **Plasma Thrusters and Flow Control**
Room: 301 B

WF2 **Magnetron Sputter Deposition**
Jyh-Ming Ting
Room: 308 AB

WF3 **Dielectic Barrier Discharges**
Hindrik de Vries, Francesco Fracassi
Room: 305 AB

WF4 **Biomedical Applications**
Farzaneh Arefi, Eun Ha Choi
Room: 303 AB

0300-0503(201510)60:9;1-O