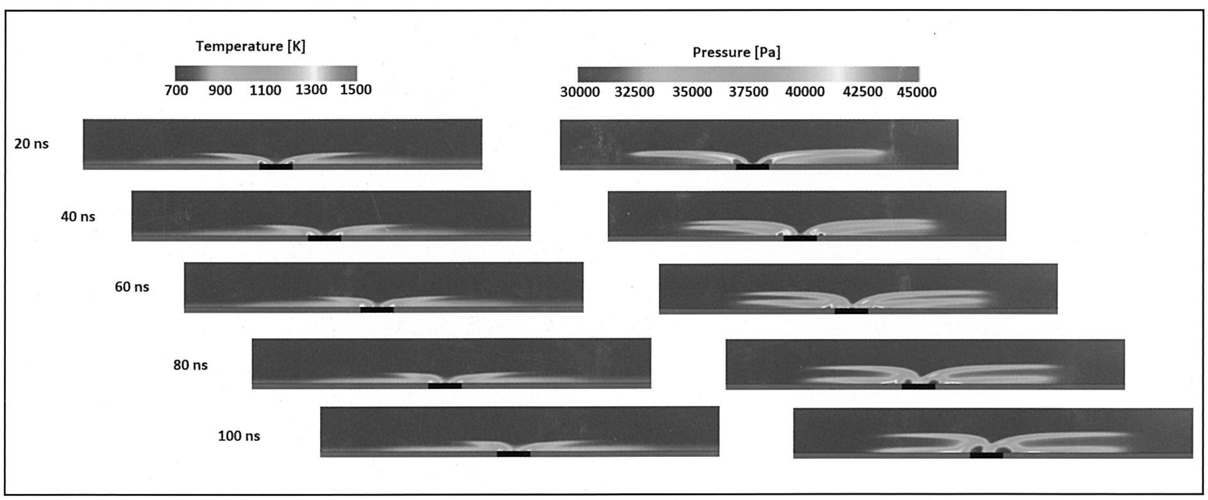
BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

65th Annual Gaseous Electronics Conference

October 22-26, 2012
Austin, Texas



Volume 57, Number 8

APS physics

BULLETIN
OF THE AMERICAN PHYSICAL SOCIETY

Coden BAPSA6 ISSN: 0003-0503
Series II, Vol. 57, No. 8 October 2012

APS MEETINGS DEPARTMENT
One Physics Ellipse
College Park, MD 20740-3844
Telephone: (301) 209-3286
Fax: (301) 209-0866
Email: meetings@aps.org
Terri Gaier, *Director of Meetings & Conventions*
Christine Lenihan, *Meeting Planner*
Ebony Montgomery, *Meetings Assistant*
Don Wise, *Senior Registrar*

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* or the "Program Changes" board located near Registration.

65th Annual
Gaseous Electronics Conference

Table of Contents

Cover image: Temperature and pressure transient induced by a nanosecond pulsed surface plasma discharge on a supersonic air flow moving from left to right. Image courtesy of: Douglas Breden and Laxminarayan Raja, University of Texas at Austin.

65th Annual
Gaseous Electronics Conference

October 2012
Austin, Texas

GENERAL INFORMATION

Welcome to Austin, Texas! Austin has a strong cultural and live music tradition and is home to international music festivals such as Austin City Limits and South By Southwest. Austin also has excellent dining options with a wide variety of international cuisines available within walking distance from the conference location. Other attractions within walking distance include free state Capitol tours conducted daily, the Bob Bullock Texas State History Museum and the university's Blanton Museum.

The 65th Gaseous Electronics Conference (GEC) of the American Physical Society is being held at the AT&T Executive Education and Conference Center, located on The University of Texas campus. The conference will bring together approximately 400 plasma scientists and engineers and will feature oral sessions and poster sessions. The GEC technical program includes the GEC Foundation Talk, two daylong preconference workshops and one evening workshop on Monday, one Tuesday evening workshop, an opening reception Monday evening, and a Thursday evening awards banquet.

GEC technical sessions will contain 34 invited talks, 243 oral contributed talks, and 165 poster presentations. The GEC will also give the "Student Award for Excellence" to the best student oral presentation.

SPECIAL SESSIONS AND EVENTS

The GEC Executive Committee is pleased to announce the GEC Foundation Talk will be presented by Klaus Bartschat from Drake University, USA. His talk entitled *Electron Collisions with Atoms, Ions, and Molecules—Experiment, Theory, and Applications* will be at 10:00 AM on Wednesday, October 24 in Amphitheatre 204.

Two daylong workshops and one evening workshop will be held on Monday, October 22.

Session AM1
Workshop on Plasma Biomedicine
Monday 8:00 am • Amphitheatre 204
Organizer: David Graves, University of California, Berkeley

Session AM2
Workshop on Plasma Cross Field Diffusion
Monday 8:30 am • Classroom 203
Organizers:
Rod Boswell, Australian National University, Australia
Igor Kaganovich, Princeton Plasma Physics Laboratory

Session AM3
Workshop on Verification and Validation of Computer Simulations in Low Temperature Plasma Physics
Monday 1:30 pm • Classroom 202
Organizers:
Miles Turner, Dublin City University, Ireland
Mirko Vukovic, Tokyo Electron

An additional evening workshop will be held on Tuesday, October 23.

Session GT2
Workshop on Plasma Data Exchange Project
Tuesday 7:00 pm • Classroom 203
Organizers:
Leanne Pitchford, University of Paul Sabatier, France
Annarita Laricchuita, CNR IMIP Bari, Italy

WORKSHOPS & RECEPTION

October 22, 2012

Session AM1 ...Workshop on Plasma Biomedicine

Session AM2 ...Workshop on Plasma Cross Field Diffusion

Session AM3 ...Workshop on Verification and Validation of Low-Temperature Plasma Simulations

Session BM1 ...Opening Reception, Interior Courtyard

GEC SESSIONS

October 23-26, 2012

Session CT1 ....Plasma Sheaths I

Session CT2 ....Plasma Surface Interactions

Session CT4 ....Microdischarges I

Session DT1 ....Diagnostics I

Session DT2 ....Low Pressure Plasma Sources

Session DT3 ....Green Plasma Technologies

Session DT4 ....Capacitively Coupled Plasmas

Session ET1 ....Nanotechnologies I

Session ET2 ....Atmospheric Pressure Nanosecond Pulsed Discharges

Session ET3 ....Inductively Coupled Plasmas

Session ET4 ....Ion Distribution Functions

Session FT1.....Biological & Biomedical Applications of Plasmas I

Session FT2.....Plasma Modeling & Simulations I

Session FT3.....Electron-Impact Ionization

Session FT4.....Advanced Laser Beam Diagnostics

Session GT2 ....Workshop on Plasma Data Exchange Project

Session HW1...Plasma Sheaths II

Session HW2...Plasma Etching I

Session HW3...Heavy Particle Collisions

Session JW1 ....GEC Foundation Talk

Session KW1...Business Meeting

Session LW1 ...Nanotechnologies II

Session LW2 ...Basic Plasma Physics Phenomena in Low-Temperature Plasmas

Session LW3 ...Plasma Propulsion I

Session MW1 ..High Pressure Discharges I

Session MW2 ..Negative Ion & Dust Particles Containing Plasmas

Session MW3 ..Collisions with Biomolecules

Session NW1...Poster Session I

Session PR1 ....Poster Session II

Session PR3 ....Positrons & Collision Processes in Plasmas

Session QR1....Plasma Modeling & Simulations II

Session QR2....Non-Equilibrium Kinetics

Session QR4....Microdischarges II

Session RR2....Thermal Plasmas: Arcs, Jets, Switches, Others

Session RR3....Plasma Propulsion II

Session RR4....Microdischarges III

Session SR1 ....Plasma Modeling & Simulations III

Session SR2 ....Plasma Etching II

Session SR3 ....Electron Collisions with Atoms & Molecules

Session SR4 ....Plasmas in Liquids

Session UF1 ....Biological & Biomedical Applications of Plasmas II

Session UF2 ....High Pressure Discharges II

Session UF3 ....Plasma Diagnostics Techniques II

Session UF4 ....Plasma Deposition & Photovoltaic Applications

CONFERENCE FORMAT

GEC will host most of its sessions on the 2nd level of the AT&T Executive Education and Conference Center. Continuous hot and cold beverages, and light refreshments will be served outside 2nd level Classrooms till 3:30 PM each day. There will be three parallel sessions Monday and Wednesday. Tuesday, Thursday, and Friday there will be four parallel sessions. The poster sessions will be held in Salon CDE on Wednesday evening and Thursday morning on the 3rd level of the conference center. WiFi is accessible throughout the AT&T Conference Center and Hotel.

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 by 8 feet. Poster sessions are on Wednesday evening and Thursday morning. Posters must be removed at the close of each poster session.

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 to present and compete for the Excellence Award. Each student award finalist will present his or her work on Wednesday, October 24. Students competing for the award, in the order of their appearance in the GEC 2012 program are:

J.P. Sheehan, University of Wisconsin
"A Kinetic Theory of Planar Plasma Sheaths Surrounding Electron Emitting Surfaces"
Amphitheatre 204
Session HW1: Plasma Sheaths II.

Sachin Sharma, Missouri University of Science & Technology
"Projectile Coherence Effects in Single & Dissociative Electron Capture in Collision of Protons with H2 & He1"
Classroom 202
Session HW3: Heavy Particle Collisions.

Sang-Heon Song, University of Michigan
"Control of Electron Energy Distributions Through Interaction of Electron Beams and the Bulk in Capacitively Coupled Plasmas"
Classroom 203
Session LW2: Basic Plasma Physics Phenomena in Low-Temperature Plasmas.

Fabien Tholin, Laboratory E.M2.C, Ecole Centrale Paris, France
"Simulation of the ignition of a H2-air mixture at atmospheric pressure by a nanosecond repetitively pulsed discharge"
Amphitheatre 204
Session MW1: High Pressure Discharges I.

Jerome Bredin, Laboratoire de Physique des Plasmas (LPP), Ecole Polytechnique/CNRS, France
"Measurements of Positive and Negative Energy Distribution Function Obtained from a Langmuir Probe in an Ion-Ion Plasma"
Classroom 203
Session MW2: Negative Ion and Dust Particle Containing Plasmas.

At GEC 2011 in Salt Lake City, the award was presented to Uttam Chowdhury, Missouri University of Science and Technology, for the oral presentation *"Fully Differential Cross Section for Four-body Charge Exchange Processes."*

REGISTRATION

The registration desk will be open on Sunday, October 21, 2012 from 4:00 to 6:00 PM in the AT&T Conference Center, Lobby. Monday through Thursday the registration desk will be open from 7:30 AM to 4:00 PM and will be located outside Amphitheatre 204. The on-site registration fees are:

Regular Attendee.....................$550
Retired/Unemployed................$300
Student...................................$300
One-Day Attendee...................$350

OPENING RECEPTION AND BANQUET

An opening reception will be held 6:00 to 8:00 PM on Monday, October 22 in the Interior Courtyard, AT&T Conference Center. On Thursday, October 25 the banquet reception will be held at 6:00 PM in Tejas Dining followed by the banquet at 7:00 PM. The cost of the banquet is included in the registration fee. Companion banquet tickets can be purchased for $65 at the registration desk on-site through Tuesday, October 23. All conference attendees and guests are encouraged to attend. The banquet will include the Student Excellence Award presentation and will feature a keynote speaker.

WI-FI AND OTHER BUSINESS SERVICES

WiFi access is complimentary throughout the AT&T Executive Education Conference Center and Hotel. For a fee, services such as faxing, printing and photocopying are available in the Business Center located on the 2nd level of the Conference Center.

AUDIO-VISUAL EQUIPMENT

The technical sessions will be equipped with an LCD projector, amplified sound, lectern, and a white board. Laptops will be provided for the technical sessions, although speakers are advised to bring their own laptops for their talks.

DINING OPTIONS

The AT&T Conference Center has full service dining at The Carillon. Gabriel's Café opens daily around noon serving casual fare. One Twenty 5 Café opens daily at 6:30 AM with light fare and beverages to go. Downtown Austin features restaurants and shopping, all within walking distance from the Conference Center.

CALL FOR NOMINATIONS FOR GEC GENERAL AND EXECUTIVE COMMITTEES

The GEC Executive Committee (ExCom) welcomes nominations, including self-nominations, for both the General Committee (GenCom) and the ExCom. Becoming a GenCom and/or ExCom 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 ExCom. At the GEC Business Meeting nominations will be accepted to select five new members of the GEC GenCom. The GenCom meets once a year during the GEC. The ExCom 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 ExCom. The GenCom reviews all proposals and makes the final site selection. The selected host is then elected to a 3-year term on the ExCom as Secretary-Elect, then Secretary, and finally as Past Secretary.

The 2012 Business Meeting will take place on Wednesday, October 24 at 11:00 AM in Amphitheatre 204 at the AT&T Executive Education and Conference Center.

GEC 2012 EXECUTIVE COMMITTEE

Biswa Ganguly
Chair
Air Force Research Laboratory

Amy Wendt
Chair Elect
University of Wisconsin

Laxminayaran Raja
Secretary
University of Texas

Tom Kirchner
Treasurer
York University, Canada

Igor Kaganovich
Secretary Elect
Princeton Plasma Physics Laboratory

Patrick Pedrow
Past Secretary
Washington State University

Michael Brunger
DAMOP Representative
Flinders University, Australia

Vincent Donnelly
University of Houston

Ed Barnat
Sandia National Laboratories

Ralf-Peter Brinkmann
Ruhr University, Germany

Masaharu Shiratani
Kyushu University, Japan

Allison Harris
Henderson State University (Appointed)

Conference Secretary
Laxminayaran Raja
University of Texas
Phone: 512-471-4279
Email: lraja@mail.utexas.edu

GEC 2012 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 65th 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.

US Government Agencies and Laboratories

Air Force Office of Scientific Research
National Science Foundation
Sandia National Laboratories
U.S. Department of Energy

Non-government Support

Gold Sponsors:
Tokyo Electron Limited
Silver Sponsors:
Applied Materials
LAM Research
Bronze Sponsors:
Esgee Technologies Inc.
Extrel Core Mass Spectrometers
Hiden Analytical
IOP Publishing
Tech-X
In Kind Sponsors:
The University of Texas at Austin

PLEASE NOTE

The 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 "Program Changes" board located near the registration desk.

Epitome of the 65th Annual Gaseous Electronics Conference

08:00 MONDAY MORNING
22 OCTOBER 2012

AM1 **Workshop on Plasma Biomedicine**
Room: Amphitheatre 204

08:30 MONDAY MORNING
22 OCTOBER 2012

AM2 **Workshop on Plasma Cross Field Diffusion**
Room: Classroom 203

13:30 MONDAY AFTERNOON
22 OCTOBER 2012

AM3 **Workshop on Verification and Validation of Low-Temperature Plasma Simulations**
Room: Classroom 202

18:00 MONDAY EVENING
22 OCTOBER 2012

BM1 **Opening Reception**
Room: Interior Courtyard

08:00 TUESDAY MORNING
23 OCTOBER 2012

CT1 **Plasma Sheaths I**
Natalia Sternberg
Room: Amphitheatre 204

CT2 **Plasma Surface Interactions**
Room: Classroom 203

CT4 **Microdischarges I**
Toshiaki Makabe
Room: Salon DE

10:00 TUESDAY MORNING
23 OCTOBER 2012

DT1 **Diagnostics I**
Room: Amphitheatre 204

DT2 **Low Pressure Plasma Sources**
Room: Classroom 203

DT3 **Green Plasma Technologies**
Haruaki Akashi
Room: Classroom 202

DT4 **Capacitively Coupled Plasmas**
Room: Salon DE

13:30 TUESDAY AFTERNOON
23 OCTOBER 2012

ET1 **Nanotechnologies I**
Tatsuru Shirafuji
Room: Amphitheatre 204

ET2 **Atmospheric Pressure Nanosecond Pulsed Discharges**
Andrey Starikovskiy
Room: Classroom 203

ET3 **Inductively Coupled Plasmas**
Valery Godyak
Room: Classroom 202

ET4 **Ion Distribution Functions**
Merritt Funk
Room: Salon DE

15:30 TUESDAY AFTERNOON
23 OCTOBER 2012

FT1 **Biological and Biomedical Applications of Plasmas I**
Room: Amphitheatre 204

FT2 **Plasma Modeling and Simulations I**
Peter Ventzek
Room: Classroom 203

FT3 **Electron-Impact Ionization**
Lorenzo Ugo Ancarani, Allan Stauffer
Room: Classroom 202

FT4 **Advanced Laser Beam Diagnostics**
Jose Maria Palomares Linares, Walter Lempert
Room: Salon DE

18:00 TUESDAY EVENING 23 OCTOBER 2012

GT1 **A Scientific Tribute to Professor Lev D. Tsendin**
Room: Classroom 202

19:00 TUESDAY EVENING 23 OCTOBER 2012

GT2 **Workshop on Plasma Data Exchange Project**
Room: Classroom 203

08:00 WEDNESDAY MORNING 24 OCTOBER 2012

HW1 **Plasma Sheaths II**
Karl-Ulrich Riemann
Room: Amphitheatre 204

HW2 **Plasma Etching I**
Lawrence Overzet
Room: Classroom 203

HW3 **Heavy Particle Collisions**
Daniel Fischer
Room: Classroom 202

10:00 WEDNESDAY MORNING 24 OCTOBER 2012

JW1 **GEC Foundation Talk**
Klaus Bartschat
Room: Amphitheatre 204

11:00 WEDNESDAY MORNING 24 OCTOBER 2012

KW1 **Business Meeting**
Room: Amphitheatre 204

13:30 WEDNESDAY AFTERNOON 24 OCTOBER 2012

LW1 **Nanotechnologies II**
Makoto Kambara
Room: Amphitheatre 204

LW2 **Basic Plasma Physics Phenomena in Low-Temperature Plasmas**
Room: Classroom 203

LW3 **Plasma Propulsion I**
Room: Classroom 202

15:30 WEDNESDAY AFTERNOON 24 OCTOBER 2012

MW1 **High Pressure Discharges I**
Ute Ebert
Room: Amphitheatre 204

MW2 **Negative Ion and Dust Particle Containing Plasmas**
Ursel Fantz
Room: Classroom 203

MW3 **Collisions with Biomolecules**
Thomas Orlando, Marcio Varella
Room: Classroom 202

19:00 WEDNESDAY EVENING 24 OCTOBER 2012

NW1 **Poster Session I (7:00-9:30PM)**
Room: Salon CDE

**08:00 THURSDAY MORNING
25 OCTOBER 2012**

PR1 **Poster Session II (8:00-10:00AM)**
Room: Salon CDE

**10:00 THURSDAY MORNING
25 OCTOBER 2012**

PR3 **Positrons and Collision Processes in Plasmas**
Ron White, David Cassidy
Room: Classroom 202

**10:30 THURSDAY MORNING
25 OCTOBER 2012**

QR1 **Plasma Modeling and Simulations II**
Jan van Dijk
Room: Amphitheatre 204

QR2 **Non-equilibrium Kinetics**
Room: Classroom 203

QR4 **Microdischarges II**
Pascal Chabert
Room: TBD

**13:30 THURSDAY AFTERNOON
25 OCTOBER 2012**

RR2 **Thermal Plasmas: Arcs, Jets, Switches, Others**
Room: Classroom 203

RR3 **Plasma Propulsion II**
Yevgeny Raitses
Room: Classroom 202

RR4 **Microdischarges III**
Leanne Pitchford
Room: Salon DE

**15:30 THURSDAY AFTERNOON
25 OCTOBER 2012**

SR1 **Plasma Modeling and Simulations III**
Denis Eremin
Room: Amphitheatre 204

SR2 **Plasma Etching II**
Joelle Margot, Tetsuya Tatsumi
Room: Classroom 203

SR3 **Electron Collisions with Atoms and Molecules**
Leigh Hargreaves, Hidetoshi Kato
Room: Classroom 202

SR4 **Plasmas in Liquids**
Room: Salon DE

**09:00 FRIDAY MORNING
26 OCTOBER 2012**

UF1 **Biological and Biomedical Applications of Plasmas II**
Room: Classroom 107

UF2 **High Pressure Discharges II**
Room: Classroom 203

UF3 **Plasma Diagnostics Techniques II**
Room: Classroom 202

UF4 **Plasma Deposition and Photovoltaic Applications**
Ante Hecimovic
Room: Salon DE

SESSION AM1: WORKSHOP ON PLASMA BIOMEDICINE

Monday Morning, 22 October 2012
Room: Amphitheatre 204 at 8:00
David Graves, University of California Berkeley, and Mark Kushner, University of Michigan, presiding

8:00
AM1 1 Introduction DAVID GRAVES, *University of California, Berkeley*

8:05
AM1 2 Plasma Biomedicine Workshop M. KONG, *Loughborough University*

8:35
AM1 3 Plasma Medicine: Current Achievements and Future Prospects MOUNIR LAROUSSI, *Old Dominion University* Research on the biomedical applications of low temperature plasmas started with small scale experiments that were simply aimed at discovering what happens to biological cells when exposed to the chemically rich environment of plasma. These early experiments took place in the mid to late 1990s. As interest in this multidisciplinary field dramatically rose, various engineering and physics groups collaborated with biologists and medical experts to investigate the use of plasma technology as a basis for innovative medical approaches to cure various diseases. However, many questions concerning the fundamental mechanisms involved in cell-plasma interaction remained unanswered. As a result various workshops were organized to gather the diverse research community in the field of plasma medicine in order to have a fruitful exchange of ideas regarding the scientific challenges that needed to be surmounted to advance and expand the field's knowledge base. The present GEC workshop continues this important tradition of scientific cooperation since there is still a significant lack of understanding of many of the biochemical and molecular pathways that come into play when biological cells are exposed to plasmas. In this talk, first background information on the various plasma devices developed in our institute will be presented. This will be followed by a summary of our work on the effects of plasmas on prokaryotic and eukaryotic cells. The talk will be concluded by presenting our vision of the future of the field and an outline of the main challenges that need to be overcome if practical medical applications are to be achieved.

9:05
AM1 4 Plasma medicine in the Netherlands GERRIT KROESEN, *Eindhoven University of Technology* Eindhoven, the Netherlands was one of the locations were Plasma Medicine originated: Eva Stoffels was one of the founders of the field. Since then, the attention for the field steadily increased. Nowadays, strong collaborations exist between the Eindhoven University of Technology (TU/e) and the Red Cross Burn Wound Hospital in Beverwijk, the Amsterdam Medical Center, the Maxima Medical Center in Eindhoven, the Radboud University in Nijmegen, the Free University in Amsterdam, and also companies, both large industries (Philips) and SME's (Vabrema, Lavoisier, Plastech). At TU/e we focus on the plasma itself: developing real time non-invasive diagnostics like TALIF, LIF, IF absorption, Thomson, Rayleigh and Raman scattering, mass spectroscopy, etc, while at the same time developing numerical models on the MD2D platform. For the biology, microbiology and medical aspects we rely on our colleagues who have specialized in those areas. Lesions that are studied are burn wounds, permanent inflammations, diabetic feet, skin infections, and internal diseases like Crohn's disease.

9:35
AM1 5 BREAK

9:50
AM1 6 Tailoring non-equilibrium atmospheric pressure plasmas for healthcare technologies TIMO GANS, *University of York* Non-equilibrium plasmas operated at ambient atmospheric pressure are very efficient sources for energy transport through reactive neutral particles (radicals and metastables), charged particles (ions and electrons), UV radiation, and electro-magnetic fields. This includes the unique opportunity to deliver short-lived highly reactive species such as atomic oxygen and atomic nitrogen. Reactive oxygen and nitrogen species can initiate a wide range of reactions in biochemical systems, both therapeutic and toxic. The toxicological implications are not clear, e.g. potential risks through DNA damage. It is anticipated that interactions with biological systems will be governed through synergies between two or more species. Suitable optimized plasma sources are improbable through empirical investigations. Quantifying the power dissipation and energy transport mechanisms through the different interfaces from the plasma regime to ambient air, towards the liquid interface and associated impact on the biological system through a new regime of liquid chemistry initiated by the synergy of delivering multiple energy carrying species, is crucial. The major challenge to overcome the obstacles of quantifying energy transport and controlling power dissipation has been the severe lack of suitable plasma sources and diagnostic techniques. Diagnostics and simulations of this plasma regime are very challenging; the highly pronounced collision dominated plasma dynamics at very small dimensions requires extraordinary high resolution - simultaneously in space (microns) and time (picoseconds). Numerical simulations are equally challenging due to the inherent multi-scale character with very rapid electron collisions on the one extreme and the transport of chemically stable species characterizing completely different domains. This presentation will discuss our recent progress actively combining both advance optical diagnostics and multi-scale computer simulations.

10:20
AM1 7 Plasma Biomedicine in Orthopedics SATSOHI HAMAGUCHI, *Osaka University* Various effects of plasmas irradiation on cells, tissues, and biomaterials relevant for orthopedic applications have been examined. For direct application of plasmas to living cells or tissues, dielectric barrier discharges (DBDs) with helium flows into ambient air were used. For biomaterial processing, on the other hand, either helium DBDs mentioned above or low-pressure discharges generated in a chamber were used. In this presentation, plasma effects on cell proliferation and plasma treatment for artificial bones will be discussed. First, the conditions for enhanced cell proliferation in vitro by plasma applications have been examined. The discharge conditions for cell proliferation depend sensitively on cell types. Since cell proliferation can be enhanced even when the cells are cultured in a plasma pre-treated medium, long-life reactive species generated in the medium by plasma application or large molecules (such as proteins) in the medium modified by the plasma are likely to be the cause of cell proliferation. It has been found that there is strong correlation between (organic) hydroperoxide generation and cell proliferation. Second, effects of plasma-treated artificial bones made of porous hydroxyapatite (HA) have been

examined in vitro and vivo. It has been found that plasma treatment increases hydrophilicity of the surfaces of microscopic inner pores, which directly or indirectly promotes differentiation of mesenchymal stem cells introduced into the pores and therefore causes faster bone growth. The work has been performed in collaboration with Prof. H. Yoshikawa and his group members at the School of Medicine, Osaka University.

10:50
AM1 8 On non-equilibrium atmospheric pressure plasma jets and plasma bullet* XINPEI LU, *CEEE, Huazhong Univ. Sci. Technol.* Because of the enhanced plasma chemistry, atmospheric pressure nonequilibrium plasmas (APNPs) have been widely studied for several emerging applications such as biomedical applications. For the biomedical applications, plasma jet devices, which generate plasma in open space (surrounding air) rather than in confined discharge gaps only, have lots of advantages over the traditional dielectric barrier discharge (DBD) devices. For example, it can be used for root canal disinfection, which can't be realized by the traditional plasma device. On the other hand, currently, the working gases of most of the plasma jet devices are noble gases or the mixtures of the noble gases with small amount of O_2, or air. If ambient air is used as the working gas, several serious difficulties are encountered in the plasma generation process. Amongst these are high gas temperatures and disrupting instabilities. In this presentation, firstly, a brief review of the different cold plasma jets developed to date is presented. Secondly, several different plasma jet devices developed in our lab are reported. The effects of various parameters on the plasma jets are discussed. Finally, one of the most interesting phenomena of APNP-Js, the plasma bullet is discussed and its behavior is described. References.

*The work is partially supported by the National Natural Science Foundation (Grant No. 10875048, 51077063), Research Fund for the Doctoral Program of Higher Education of China (20100142110005), and Chang Jiang Scholars Program, Ministry of Education.

[1]X. Lu, M. Laroussi, and V. Puech, Plasma Sources Sci. Technol. **21**, 034005 (2012).
[2]Y. Xian, X. Lu, S. Wu, P. Chu, and Y. Pan, Appl. Phys. Lett. **100**, 123702 (2012).
[3]X. Pei, X. Lu, J. Liu, D. Liu, Y. Yang, K. Ostrikov, P. Chu, and Y. Pan, J. Phys. D **45**, 165205 (2012).

11:20
AM1 9 Control of the Proliferation of Mammalian Cells by the Non-Thermal Atmospheric Pressure Plasmas* HAE JUNE LEE, CHANG SEUNG HA, *Pusan National University* YONG-HAO MA, *Yonsei University* JUNGYEOL LEE, *Pusan National University* KIWON SONG, *Yonsei University* Recent development of the atmospheric pressure plasmas (APPs) reported dramatic achievement on the applications to sterilization, wound healing, blood coagulation, and so on. These effects are coming from the abundant electrons, various ions, radicals, and neutral atoms which cause specific interactions with cells. However, the application of APPs to human cells has been mainly focused on cell death, but not so much on cell proliferation. In this study, the effects of a non-thermal dielectric barrier discharge (DBD) were investigated for three different human cell lines. It was observed that the exposure of APP to human adipose-derived stem cells (ASC) and the primary lung fibroblast IMR-90 cells induced increased cell proliferation in a specific condition. On the other hand, the same exposure of APP to HeLa cells dramatically decreased their viability. These observations suggest that different types of human cells differentially respond to the exposure of APP.

*This work was supported by Korean Research Institute for Chemical Technology (KRICT) funded by Ministry of Knowledge Economy, Korea.

11:50
AM1 10 LUNCH BREAK

12:50
AM1 11 plasmatis Center for Innovation Competence: Controlling reactive component output of atmospheric pressure plasmas in plasma medicine* STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* The novel approach of using plasmas in order to alter the local chemistry of cells and cell environment presents a significant development in biomedical applications. The plasmatis center for innovation competence at the INP Greifswald e.V. performs fundamental research in plasma medicine in two interdisciplinary research groups. The aim of our plasma physics research group "Extracellular Effects" is (a) quantitative space and time resolved diagnostics and modelling of plasmas and liquids to determine distribution and composition of reactive species (b) to control the plasma and apply differing plasma source concepts in order to produce a tailored output of reactive components and design the chemical composition of the liquids/cellular environment and (c) to identify and understand the interaction mechanisms of plasmas with liquids and biological systems. Methods to characterize the plasma generated reactive species from plasma-, gas- and liquid phase and their biological effects will be presented. The diagnostic spectrum ranges from absorption/emission/laser spectroscopy and molecular beam mass spectrometry to electron paramagnetic resonance spectroscopy and cell biological diagnostic techniques. Concluding, a presentation will be given of the comprehensive approach to plasma medicine in Greifswald where the applied and clinical research of the Campus PlasmaMed association is combined with the fundamental research at plasmatis center.

*Funded by the German Federal Ministry of Education and Research.

13:20
AM1 12 Antitumor action of non thermal plasma sources, DBD and Plasma Gun, alone or in combined protocols* ERIC ROBERT, *GREMI UMR7344 CNRS/Université d'Orléans* LAURA BRULLÉ, *TAAM-CIPA UPS44 CNRS Orléans* MARC VANDAMME, *TAAM-CIPA UPS44 CNRS Orléans and GREMI UMR7344 CNRS/Université d'Orléans* DELPHINE RIÈS, *GREMI UMR7344 CNRS/Université d'Orléans* ALAIN LE PAPE, *TAAM-CIPA UPS44 CNRS Orléans* JEAN-MICHEL POUVESLE, *GREMI UMR7344 CNRS/Université d'Orléans* The presentation deals with the assessment on two non thermal plasma sources developed and optimized for oncology applications. The first plasma source is a floating-electrode dielectric barrier discharge powered at a few hundreds of Hz which deliver air-plasma directly on the surface of cell culture medium in dishes or on the skin or organs of mice bearing cancer tumors. The second plasma source, so called Plasma Gun, is a plasma jet source triggered in noble gas, transferred in high aspect ratio and flexible capillaries, on targeting cells or tumors after plasma transfer in air through the "plasma plume" generated at the capillary outlet. *In vitro* evidence for massive cancer cell destruction and *in vivo* tumor activity and growth rate reductions have been measured with both plasma sources. DNA damages, cell

cycle arrests and apoptosis induction were also demonstrated following the application of any of the two plasma source both *in vitro* and *in vivo*. The comparison of plasma treatment with state of the art chemotherapeutic alternatives has been performed and last but not least the benefit of combined protocols involving plasma and chemotherapeutic treatments has been evidenced for mice bearing orthotopic pancreas cancer and is under evaluation for the colon tumors.

*Work supported by APR "PLASMED" and ANR BLAN "PAMPA" 093003.

13:50
AM1 13 Comparing plasma and X-ray exposure and identifying vulnerable cell parts* BILL GRAHAM, *Queen's University Belfast* Here two issues in plasma medicine that are being addressed in a collaboration between the Centre of Plasma Physics and the School of Pharmacy at Queen's University Belfast and the Plasma Institute at York University UK will be discussed. Recent measurements of the interaction of plasmas created directly in DMEM cell medium and MDAMB-231, a human breast cancer cell line, showed evidence of reduced cell viability and of DNA damage. The same set of experiments were undertaken but with X-ray exposure. A correlation of the dependence on plasma exposure time and X-ray dose was observed which might point the way to dose definition in plasma medicine. We have also been working to identify the cell parts most vulnerable to plasma exposure. In this study a 10 kHz atmospheric pressure non-thermal plasma jet, operating in $He/0.5\%O_2$ and characterized to determine the behavior of many of the plasma species, was incident onto the surface of media containing either bacterial strains, in their planktonic and biofilm forms, or isolated bacterial plasmid DNA. The results of measurements to look for changes in plasmid structural conformation, rates of single and double strand breaks, the catalytic activity of certain bacterial enzymes, the peroxidation of lipid content of the bacterial cells, the leakage of ATP and Scanning Electron Microscope (SEM) images will be discussed.

*Supported in part by UK EPSRC Science and Innovation Grant.

14:20
AM1 14 BREAK

14:35
AM1 15 Roundtable: How to characterize/compare/benchmark sources?

SESSION AM2: WORKSHOP ON PLASMA CROSS FIELD DIFFUSION
Monday Morning, 22 October 2012
Room: Classroom 203 at 8:30
Rod Boswell, Australian National University and Igor Kaganovich, Princeton Plasma Physics Laboratory, presiding

8:30
AM2 1 Introduction

8:45
AM2 2 Expansion of a plasma across a transverse magnetic field in a negative hydrogen ion source for fusion URSEL FANTZ, LOIC SCHIESKO, DIRK WÜNDERLICH, *Max-Planck-Institut für Plasmaphysik* NNBI TEAM Negative ion sources are a key component of the neutral beam injection systems for the international fusion experiment ITER. To achieve the required ion current of 40 A at a tolerable amount of co-extracted electrons (electron to ion ratio below one) the source is separated into a plasma generation region and an expansion chamber equipped with a magnetic filter field (up to 10 mT). The field is needed for: (1) cooling the electrons down and thus minimize the H^- destruction by collisions, (2) to reduce the co-extracted electron current, and (3) to enhance the extraction probability for the surface produced negative ions. The area of the ITER source will be approximately 1m width and 2 m height, the IPP prototype source is a 1/8-size source. The recently installed flexible magnetic filter frame allows for systematic filter field studies (strength, position, polarity). Two Langmuir probes have been used to measure the plasma parameters simultaneously in axial direction. The profiles in the upper and lower part of the expansion chamber show beside the expected electron temperature and density decrease a drop in the plasma potential and a drift depending on the polarity, which vanishes when removing the filter field. The data interpretation is supported by modeling activities.

9:15
AM2 3 Modeling plasma transport across the magnetic filter of the ITER negative ion source* G.J.M. HAGELAAR, F. GABORIAU, G. FUBIANI, B. CHAUDHURY, J.P. BOEUF, *LAPLACE, CNRS and Univ Toulouse* This presentation gives an overview of numerical modeling work at LAPLACE Toulouse on the negative filter operation of the ITER negative ion source developed at IPP Garching [U. Fantz *et al.*, Rev. Sci. Instrum. 79, 02A511 (2008)]. The magnetic filter separates the source driver region (where plasma is produced by an inductive RF discharge) from the low electron temperature region in front of the extraction grids (where negative ions are produced and extracted from the plasma). The plasma transport across the filter is a key issue for the source performance. Both fluid and particle-in-cell models have been developed in order to improve fundamental understanding of this transport. The models demonstrate the dominant role of magnetic drift, increasing the cross field transport and inducing asymmetry in the plasma. Plasma instabilities are also observed but presumably do not contribute significantly to the cross field transport. A dedicated experimental set-up is under construction in order to obtain additional data to test and validate the models.

*This work is supported by the French National Research Agency (project METRIS ANR-11-JS09-008) and by EFDA, CEA, and the Federation de Recherche sur la Fusion Magnetique.

9:30
AM2 4 An Overview of Negative Ion Beams and Sources ROBERT WELTON, *Oak Ridge National Laboratory* This report will provide a broad introduction to the field of negative ion beams and sources first by summarizing their use in scientific research and industrial applications ranging from thermonuclear fusion, high energy physics, nuclear physics, neutron production, organic mass spectroscopy, accelerator mass spectroscopy, radioactive ion beam generation and others. Specific examples of important light and heavy ion negative sources will be discussed as well as the physics of negative ion formation. Finally, a summary of the recent 3rd International Symposium on Negative Ions, Beams and Sources in

Jyvaskyla, Finland will be presented identifying some of the most important issues currently facing the field.

10:00

AM2 5 A High Brightness Negative Ion Source for SIMS NOEL SMITH, *Oregon Physics LLC* ROD BOSWELL, *Australian National University* PAUL TESCH, NOEL MARTIN, *Oregon Physics LLC* Secondary ion mass spectrometry (SIMS) often utilizes a negative oxygen (O^- or O_2^-) focused ion beam for trace element analysis of materials. The primary advantage of SIMS over other mass spectrometric techniques is the ability to provide spatial information in addition to high detection sensitivity. However, the scanned ion image resolution of these instruments is limited by the performance of the ion source employed to create the focused primary ion beam. To date, the duoplasmatron ion source has been the most suitable source of negatively charged oxygen ions, with an energy normalized brightness (β_r) for O^- of ~40 $Am^{-2}sr^{-1}V^{-1}$ and an energy spread (ΔE) of ~10–15 eV. This produces imaging resolution in the range of 1–30 μm for the ASI SHRIMP and Cameca 1280 tools and an impressive 150 nm spot size for the NanoSIMS 50. Here we describe a newly developed inductively coupled plasma source with negative ion extraction. This source has $\beta_r = 600$ $Am^{-2}sr^{-1}V^{-1}$ and ΔE of only 3.5 eV for O^- ion extraction. This translates to a nominal 100x gain in current density in the focused beam, when operated for high resolution imaging.

10:15

AM2 6 Electron temperature and plasma density distribution measurement along magnetic barrier in the PEGASES thruster* JEROME BREDIN, ANE AANESLAND, PASCAL CHABERT, *Laboratoire de Physique des Plasma (LPP), Ecole Polytechnique/CNRS, Route de Saclay, 91128 Palaiseau, France* VALERY GODYAK, *RF Plasma Consulting, Brookline, Massachusetts 02446, USA* The basic plasma parameter, electron temperature and plasma density were found as corresponding integrals of the measured EEDF in the PEGASES thruster. The measurements were carried out along the axis and off-axis of the magnetic barrier created with permanent magnets having their magnetic field lines normal to the plasma expansion. The plasma was generated with an induction coil on one end of the thruster, and diffused across magnetic field to the exit of the thruster. The experiments in argon gas were carried out for various parameters of magnetic field (strength, position and gradient). Previously, we showed that the electron temperature can be controlled by the magnetic field, and the degree of the temperature control depends on the gas pressure. In this study we measured the temperature off-axis to understand the influence of the wall conductivity on the electron transport across and along magnetic field. The off-axis probe measurements showed fine structures in the electron temperature and plasma density spatial distributions. A possible mechanism of the structures in the plasma density and the electron temperature distributions are discussed in this presentation.

*This work is part of the PEGASES project funded by EADS Astrium and the EPIC-ANR blanc project ANR-11-BS09-040. V. Godyaks work was supported in part by the DOE OFES (Contract No DE-SC0001939).

10:30

AM2 7 BREAK

11:00

AM2 8 Cross-field diffusion in Hall thrusters and other plasma thrusters J.P. BOEUF, *LAPLACE, Universite de Toulouse, France* Understanding and quantifying electron transport perpendicular to the magnetic field is a challenge in many low temperature plasma applications. Hall effect thrusters (HETs) provide an excellent example of cross-field transport. The HET is a very successful concept that can be considered both as a gridless ion source and an electromagnetic thruster. In HETs, the electric field E accelerating the ions is a consequence of the Lorentz force due to an external magnetic field B acting on the $E \times B$ Hall electron current. An essential aspect of HETs is that the $E \times B$ drift is closed, i.e. is in the azimuthal direction of a cylindrical channel. In the first part of this presentation we will discuss the physics of cross-field electron transport in HETs, and the current understanding (or non-understanding) of the possible role of turbulence and wall collisions on cross-field diffusion. We will also briefly comment on alternative designs of ion sources based on the same principles as the conventional HET (Anode Layer Thruster, Diverging Cusp Field Thrusters, End-Hall ion sources). In a second part of the presentation we show that the Lorentz force acting on diamagnetic currents (associated with the $\nabla P_e \times B$ term in the electron momentum equation) can also provide thrust. This is the case for example in helicon thrusters where the plasma expands in a magnetic nozzle. We will report and discuss recent work on helicon thrusters and other devices where the diamagnetic current is dominant (with some examples where the $\nabla P_e \times B$ current is not closed and is directed toward a wall!).

11:30

AM2 9 Cross-Field Transport of Electrons in Hall Plasma Accelerators* MARK A. CAPPELLI, *Stanford University* The transport of electrons across the magnetic field within the channel of a Hall discharge plasma accelerator is still the subject of much research. Experiments [1] have shown that the electron mobility is greater than can be accounted for by elastic scattering with neutrals. A number of models have been proposed but the mechanism for this anomalous transport is still heavily debated. In this presentation, we will review the measurements and discuss the mechanisms proposed, including collisions with channel walls and instabilities. We will also present past attempts at incorporating transport models into numerical simulations of Hall plasma thrusters used in space propulsion.

*Supported by the Air Force Office of Scientific Research.

[1]Meezan *et al.*, Phys. Rev. E **63**, 026410 (2001).

11:45

AM2 10 Effect of Secondary Electron Emission on Electron Cross-Field Current in $E \times B$ Discharges YEVGENY RAITSES, IGOR D. KAGANOVICH, ALEX V. KHRABROV, MICHAEL D. CAMPANELL, ERINC TOKLUOGLU, *Princeton Plasma Physics Laboratory* DMYTRO SYDORENKO, *University of Alberta* ANDREI SMOLYAKOV, *University of Saskatchewan* This paper reviews recent experimental, theoretical, and numerical studies of plasma-wall interaction in a weakly collisional magnetized plasma bounded with channel walls made from different materials [1–3]. A low-pressure $E \times B$ plasma discharge of the Hall thruster was used to characterize the electron current across the magnetic field and its dependence on the applied voltage and the electron-induced secondary electron emission (SEE) from the channel wall [1]. The presence of a depleted anisotropic electron energy distribution function with beams of secondary electrons was predicted to explain the enhancement of the electron cross-field current observed in experiments. Without the SEE, the electron cross-field transport can be reduced from anomalously high to nearly classical collisional level. The suppression of the SEE was achieved using an engineered carbon-velvet material for the channel walls [3]. Both theoretically and experimentally, it is shown that the electron emission from the walls can limit the maximum achievable electric field in the magnetized plasma.

[1]Y. Raitses *et al.*, IEEE Trans. on Plasma Scie. **39**, 995 (2011).
[2]M. D. Campanell *et al.*, Phys. Rev. Lett. **108**, 235001 (2012).
[3]Y. Raitses *et al.*, J. Appl. Phys. **99**, 036103 (2006).

12:00
AM2 11 Centripetal force and neutral-gas depletion effects on cross-field transport* AMNON FRUCHTMAN, *H.I.T. - Holon Institute of Technology* NATHANIEL J. FISCH, YEVGENY RAITSES, *PPPL, Princeton University* Two issues related to diffusion across magnetic field lines are discussed. The first issue is an electron rotating flow in crossed electric and magnetic fields in the z-r plane, for which it was recently shown that due to the centripetal force magnetic field surfaces do not coincide with equipotential surfaces [1]. An exact particular solution of the governing equations will be presented for the two-dimensional electron flow and for the electric potential. This deviation of equipotential surfaces will be shown to affect the divergence of the plasma beam exiting the Hall thruster. Moreover, that deviation will be shown to explain the low beam divergence in the cylindrical Hall thruster. The second issue is the different roles that neutral-gas depletion plays when the cross-field diffusion is ambipolar and when it is not [2]. Electrons have to cross field lines when the flow is ambipolar, and their collisions with neutral atoms enhance the cross-field diffusion. When the flow in nonambipolar, electrons leave the discharge along field lines. The often-unmagnetized ions then perform a cross-field transport which is impeded by collisions with neutral atoms. Neutral-gas depletion therefore reduces the cross-field transport if the flow is ambipolar and enhances the cross-field transport if the flow is nonambipolar.

*Supported by the Israel - US BSF under Grant No 2008224.

[1]N. J. Fisch, Y. Raitses, and A. Fruchtman, Plasma Phys. Control. Fusion **53**, 124038 (2011).
[2]A. Fruchtman, Plasma Sci. Technol. **18**, 025033 (2009).

12:15
AM2 12 Bull Ring Discussion

12:45
AM2 13 BREAK

14:00
AM2 14 Reminder of Rules

14:10
AM2 15 Modification of turbulent transport with continuous variation of flow shear in the Large Plasma Device* TROY CARTER, DAVID SCHAFFNER, GIOVANNI ROSSI, DANIEL GUICE, JIM MAGGS, STEPHEN VINCENA, BRETT FRIEDMAN, *UCLA* The LArge Plasma Device (LAPD) at UCLA is a 17 m long, 60 cm diameter magnetized plasma column with typical plasma parameters $n_e \sim 1 \times 10^{12}$ cm^{-3}, $T_e \sim 10$ eV, and $B \sim 1$ kG. Broadband, fully-developed turbulence is observed in the edge of the LAPD plasma along with spontaneously driven azimuthal flows. Recently, the capability to continuously vary the edge flow and flow shear has been developed in LAPD using biasing of an annular limiter. Spontaneous flow is observed in the ion diamagnetic direction (IDD), biasing tends to drive flow in the opposite direction, allowing a continuous variation of flow from the IDD to the electron diamagnetic direction, with a near-zero flow and flow shear state achieved along the way. Enhanced confinement and density profile steepening is observed with increasing shearing rate; degraded confinement is observed when spontaneous flow is nulled-out and near-zero shear is acheived. Particle flux and radial correlation length are observed to decrease with increasing shear. The decrease occurs with shearing rates which are comparable to the inverse turbulent autocorrelation time in the zero flow state.

*Work supported by NSF Grant PHY0903913 and was performed using the Basic Plasma Science Facility which is supported by NSF and DOE.

14:25
AM2 16 Radial transport in bounded cylinders and physics of "universal" profiles FRANCIS F. CHEN, *UCLA* Even strong magnetic fields cannot confine electrons radially in a cylinder if the cylinder length is defined by endplates that are not far apart. The sheaths on the endplates will adjust themselves to allow the electron density n to "follow" the radial electric field, even though the electrons are actually lost to the ends, not to the sidewall. This nanosecond mechanism allows electrons to follow the Boltzmann relation, even across the B-field. If the plasma is ionized near the wall, the ions will be driven inwards by the resulting E-field, which is scaled to T_e. Thus, the (weakly magnetized) ions will reach the center faster than at their thermal velocities. When equilibrium is reached, the field is reversed to push the ions outward to the sidewall, their closest escape path. Under these conditions, n is always peaked on axis. A detailed treatment* of this problem yields the surprising fact that the density and potential profiles in equilibrium are independent of neutral pressure and cylinder radius, varying only with T_e. A simple physical argument shows why this has to be true.

*D. Curreli and F. F. Chen, Phys. Plasmas **18**, 113501 (2011).

14:45
AM2 17 Turbulence-induced anomalous electron diffusion in the plume of the VASIMR VX-200 CHRISTOPHER OLSEN, MAXWELL BALLENGER, JARED SQUIRE, BENJAMIN LONGMIER, MARK CARTER, TIM GLOVER, *Ad Astra Rocket Company* The separation of electrons from magnetic nozzles is critical to the function of the VASIMR engine and is of general importance to the field of electric propulsion. Separation of electrons by means of anomalous cross field diffusion is considered. Plume measurements using spectral analysis of custom high frequency probes characterizes the nature of oscillating electric fields in the expanding magnetic nozzle. The oscillating electric field results in frequency dependent density variations that can lead to anomalously high transport in the absence of collisions mimicking collisional transport. The spatial structure of the fluctuating fields is consistent with turbulence caused by separation of energetic (>100 eV) non-magnetized ions and low energy magnetized electrons via the modified two-stream instability (MTSI) and generalized lower hybrid drift instability (GLHDI). Electric fields as high as 300 V/m are observed at frequencies up to an order of magnitude above the lower hybrid frequency. The electric field fluctuations dissipate with increasing axial distance consistent with changes in ion flux streamlines as plasma detachment occurs.

15:00

AM2 18 Particle-in-cell simulations of ambipolar and nonambipolar diffusion in magnetized plasmas ROD BOSWELL, TREVOR LAFLEUR,* *Australian National University* Using a two-dimensional particle-in-cell simulation, we investigate cross-field diffusion in lowpressure magnetized plasmas both in the presence and absence of conducting axial boundaries. With no axial boundary, the cross-field diffusion is observed to be ambipolar, as expected. However, when axial boundaries are added, the diffusion becomes distinctly nonambipolar. Electrons are prevented from escaping to the transverse walls and are preferentially removed from the discharge along the magnetic field lines, thus allowing quasi-neutrality to be maintained via a short-circuit effect at the axial boundaries.

*Presently at Ecole Polytechnique, Paris, France.

15:15

AM2 19 Cross Field Workshop WENDELL HORTON, *The University of Texas at Austin*

15:30

AM2 20 BREAK

16:00

AM2 21 Stability of spontaneously appearing ion beams in expanding plasmas EARL SCIME, JERRY CARR JR., ROBERT VANDERVORT, *West Virginia University* NJAL GULBRANDSEN, *Univesity of Tromso* We present time resolved measurements of ion beam formation in the expansion region of a pulsed helicon plasma. The ion beams are identified in ion velocity distribution function measurements obtained through laser induced fluorescence and retarding field energy analyzer diagnostics. As the plasma discharge forms, an ion beam appears and then vanishes coincident with the appearance of large amplitude electrostatic fluctuations. For a strong mirror ratio, the correlation between fluctuations in the ion population and the electrostatic fluctuations are strong. For a weak mirror ratio, the beam is less correlated with the electrostatic fluctuations than the bulk ion population and the beam persists throughout the discharge. The fluctuation measurements are analyzed using a time-resolved spectral method that provides a measurement of the fluctuation spectrum throughout a single discharge pulse. Combined with the time-resolved ion distribution function measurements, it is possible to identify which portions of the ion velocity distribution most strongly interact with the electrostatic fluctuations.

16:15

AM2 22 Electron diamagnetic effect in a magnetic nozzle on a helicon plasma thruster performance KAZUNORI TAKAHASHI, TREVOR LAFLEUR, CHRISTINE CHARLES, PETER ALEXANDER, ROD BOSWELL, *The Australian National University* The axial force, which is called thrust sometimes, imparted from a magnetically expanding helicon plasma thruster is directly measured and the results are compared with a two-dimensional fluid theory. The force component solely transmitted to the expanding field is directly measured and identified as an axial force produced by the azimuthal current due to an electron diamagnetic drift and the radial component of the applied magnetic field. In this type of configuration, plasma diffusion in magnetic field affects a spatial profile of the plasma density and the resultant axial force onto the magnetic field. It is observed that the force component onto the magnetic field increases with an increase in the magnetic field strength, simultaneously with an increase in the plasma density downstream of the source exit, which could be due to suppression of the cross field diffusion in the magnetic nozzle.

16:30

AM2 23 Characteristics of High-Density Helicon Plasma Sources and Their Application to Electrodeless Electric Propulsion* S. SHINOHARA, H. NISHIDA, T. NAKAMURA, A. MISHIO, H. ISHII, N. TESHIGAHARA, H. FUJITSUKA, S. WASEDA, *TUAT* T. TANIKAWA, *Tokai U.* T. HADA, F. OTSUKA, *Kyushu U.* I. FUNAKI, T. MATSUOKA, *JAXA* K. SHAMRAI, T. RUDENKO, *INR* High-density but low temperature helicon plasmas have been proved to be very useful for fundamental research as well as for various applications. First, we introduce our very large helicon sources [1] with a diameter up to 74 cm. For the industrial and propulsion applications, we have reduced the aspect ratio (axial length-to-diameter) down to 0.075, and examined the discharge performance and wave characteristics. Then, we discuss our small helicon sources [1] for developing new electrodeless acceleration schemes. Some experimental and theoretical results [2] by applying the rotating magnetic (or electric) fields to the helicon plasma under the divergent magnetic field will be presented, along with other propulsion schemes. In addition, an initial plasma production experiment with very small diameter will be described.

*Work partly supported by the Grant-in-Aid for Scientific Research (21226019) from JSPS.

[1] S. Shinohara *et al.*, Jpn. J. Appl. Phys. **35**, 4503 (1996); Rev. Sci. Instrum. **75**, 1941 (2004); Phys. Plasmas **16**, 057104 (2009).

[2] S. Shinohara *et al.*, *32th Int. Electric Propul. Conf.*, IEPC-2011-056, 2011.

16:45

AM2 24 Plume detachment from a magnetized plasma thruster ROGER BENGTSON, *University of Texas at Austin* High-powered electric propulsion thrusters utilizing a magnetized plasma require that plasma exhaust detach from the onboard magnetic coils in order to produce thrust. We present experimental and theoretical results demonstrating that a sufficiently powerful plasma flow does indeed detach from a magnetic nozzle. Measurements of ion flux show a low-beta plasma plume which follows applied magnetic field until the magnetic pressure falls below the plasma energy density. The plasma flow becomes super-Alfvenic at that point and it continues ballistically downstream. Several magnetic configurations were tested including a reversed field nozzle configuration. Despite the dramatic change in magnetic field profile, the reversed field configuration yielded little measurable change in plume trajectory, demonstrating the plume is detached. Numerical simulations yield density profiles in agreement with the experimental results.

17:00

AM2 25 Evidence for anomalous resistivity in a helicon plasma source BORIS BREIZMAN, *University of Texas at Austin* Measurements and modeling of the rf field structure in a helicon plasma source at UT have demonstrated that these fields represent radially localized helicon waves that propagate in the axial direction. A good agreement in the absolute amplitude and phase of the fields between measurement and simulation could only be reached by enhancing the electron Coulomb collision frequency by a factor of 30 in the simulation. We attribute the enhanced collision frequency to the excitation of an ion-acoustic instability, as the electron azimuthal diamagnetic drift exceeds the ion sound speed under the experimental conditions. This interpretation is also consistent with the observed suppression of the electron heat transport along the magnetic field lines.

17:15
AM2 26 Running of the Bulls YEVGENY RAITSES, *Princeton Plasma Physics Laboratory*

SESSION AM3: WORKSHOP ON VERIFICATION AND VALIDATION OF LOW-TEMPERATURE PLASMA SIMULATIONS
Monday Afternoon, 22 October 2012
Room: Classroom 202 at 13:30
Mirko Vukovic, Tokyo Electron Limited and Miles Turner, Dublin City University, presiding

13:30
AM3 1 Overview of Verification and Validation in Low Temperature Plasma Physics M.M. TURNER, *Dublin City University, Ireland* M. VUKOVIC, *Tokyo Electron Ltd, U.S.A.* Computational work has formed an essential part of low-temperature plasma physics research for many years. As in many other fields, there is a tendency towards more complex simulations, as physical models become more elaborate and computer hardware becomes more sophisticated. Inevitably, this means that computer codes have become more complex. Complex physical models combined with complex implementation leads to considerable difficulty in establishing the fidelity of simulation results, as the physical model may contain assumptions that have been inadvertently violated, and the computer code may contain implementation errors. One needs a methodology for finding such mistakes, and also distinguishing between these two categories of mistake. In modern parlance, accumulating evidence that simulation codes are correct is known as Verification, while the process of testing the physical model is called Validation. This paper will present an overview of some important modern ideas on how Verification and Validation should be carried out, and discuss the implications of these concepts for the practice of computer simulation in low-temperature plasma physics.

14:00
AM3 2 Verification strategies for fluid-based plasma simulation models SHANKAR MAHADEVAN, *Esgee Technologies Inc.* Verification is an essential aspect of computational code development for models based on partial differential equations. However, verification of plasma models is often conducted internally by authors of these programs and not openly discussed. Several professional research bodies including the IEEE, AIAA, ASME and others have formulated standards for verification and validation (V&V) of computational software. This work focuses on verification, defined succinctly as *determining whether the mathematical model is solved correctly*. As plasma fluid models share several aspects with the Navier-Stokes equations used in Computational Fluid Dynamics (CFD), the CFD verification process is used as a guide. Steps in the verification process: consistency checks, examination of iterative, spatial and temporal convergence, and comparison with exact solutions, are described with examples from plasma modeling. The Method of Manufactured Solutions (MMS), which has been used to verify complex systems of PDEs in solid and fluid mechanics, is introduced. An example of the application of MMS to a self-consistent plasma fluid model using the local mean energy approximation is presented. The strengths and weaknesses of the techniques presented in this work are discussed.

14:15
AM3 3 Towards the numerical verification of plasma simulation codes MIRKO VUKOVIC, *Tokyo Electron, US Holdings* To aid in verification of existing and new plasma simulation codes, we propose a suite of standard simulation problems against which a new code would be compared with. Each standard problem provides a detailed input specifications and results in forms of tables of numeric values. The problems use an idealized and simplified reaction cross-section and rates set. The problems are designed to verify individual numerical components of plasma simulation codes and the overall plasma simulation. The issue of establishing a "correct" plasma simulation result will be discussed. In addition, we will discuss the portability of these problems: the problems should be specified in a manner that can be read by simulation codes written in different languages, and executed on different platforms.

14:30
AM3 4 BREAK

15:00
AM3 5 Benchmark solutions for simulations of capacitively coupled discharges M.M. TURNER, *Dublin City University, Ireland* D. EREMIN, T. MUSSENBROCK, *Ruhr University Bochum, Germany* A. DERZSI, Z. DONKO, *Hungarian Academy of Sciences, Hungary* Benchmarks are an important element of Verification and Validation strategies. Such strategies define a process for increasing confidence in the fidelity of computer simulations, with the aim of making confident predictions of physical behaviour under conditions of practical interest. Such confidence can be increased by developing benchmark solutions for representative conditions. A benchmark solution is a high quality solution that is accepted to be correct. In this paper, we describe an attempt to develop such solutions for capacitive discharges, and we show that a number of independently developed particle-in-cell simulations can reproduce the benchmark solutions. These solutions are useful not only for particle-in-cell simulations, but also for other kinds of plasma simulations. We will show comparisons of fluid model solutions with the benchmarks.

15:15
AM3 6 Verification of Particle-in-Cell Codes for Low Temperature Plasma Physics* KEITH CARTWRIGHT, *Sandia National Laboratories* A broad overview of verification procedures for computer simulation with an emphasis in low temperature plasma physics will be presented. To have a high degree of confidence in simulations one needs code verification, code validation, solution verification, and uncertainty quantification. Code verification is a set of test developed to uncover coding mistakes that affect the numerical solution. Code validation addresses the appropriateness of the model in reproducing experimental data. Solution verification is the estimation of the numerical errors that occur in every computer simulation including validation and verification. Uncertainty quantification is the characterization of the sensitivity of results to parameters and geometry used in the models. The verification of the simulation code is an important first step in increasing the credibility of the results from simulations. Methods for generating of good verification problem for low temperature plasma physics will be shown. This includes the use of analytic solutions as well as using the method of manufactured and nearby solutions. DC sheaths with

both pure electrons and electron and ion sheaths is the verification problem that will be discussed in detail.

*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.

15:30

AM3 7 Inductively-coupled plasmas in pure chlorine: comparison experiments/HPEM* JEAN-PAUL BOOTH, NISHANT SIRSE, YASMINA AZAMOUM, PASCAL CHABERT, *LPP-CNRS, Ecole Polytechnique, France* Inductively-coupled plasmas in chlorine-based gas mixtures are widely used for etching of nanometric features in silicon for CMOS device manufacture. This system is also of considerable fundamental interest as an archetype of strongly electronegative plasmas in a simple gas, for which reliable techniques exist to measure the densities of all key species. As such, it is an ideal test-bed for comparison of simulations to experiment. We have developed a technique based on two-photon Laser-Induced Fluorescence to determine the absolute Cl atom density. The Cl surface recombination coefficient was determined from time-resolved measurements in the afterglow. Electron densities were determined by microwave hairpin resonator and EEDF's were measured by Langmuir probe. Whereas the HPEM results were in good agreement at lower pressures (below 10mTorr), electron densities are increasingly underestimated at higher pressures. The gas temperature was measured by Doppler-resolved Infra-red Laser Absorption spectroscopy of Ar metastable atoms (with a small fraction Ar added). At higher pressures the gas temperature was considerably underestimated by the model. The concomitant overestimation of the gas density is a major reason for the disagreement between model and experiment.

*Partially supported by ANR-09 BLAN 0019 and Applied Materials.

15:45

AM3 8 Breakdown voltage calculations using PIC-DSMC PAUL CROZIER, JEREMIAH BOERNER, MATTHEW HOPKINS, CHRISTOPHER MOORE, LAWRENCE MUSSON, *Sandia National Laboratories* In general, modeling and simulation provide physical insight and enable extrapolative predictions beyond theory and experimental data. In the specific case of electrostatic discharges, modeling and simulation may enable extrapolative predictions of breakdown voltages and a better physical understanding of breakdown phenomena. Using our PIC-DSMC software, we compute breakdown voltages for molecular nitrogen gas and compare our results against Bolsig+ for simple 1D geometries. We further verify our breakdown voltage calculations for a simple 3D geometry. In these calculations, 25 different N_2 – electron interactions are included and good agreement with Bolsig+ is observed. Our approach to computing breakdown voltages using PIC-DSMC software can be extended to the prediction of breakdown voltages in more difficult cases where experimental data may be unavailable and the Paschen equation assumptions are no longer valid, as in the cases of complex 3D geometries and microscale discharges.

16:00

AM3 9 Wrap-up/Discussion

SESSION CT1: PLASMA SHEATHS I
Tuesday Morning, 23 October 2012; Room: Amphitheatre 204 at 8:00; Peter Ventzek, Tokyo Electron Limited, presiding

Invited Papers

8:00
CT1 1 Plasma-Sheath Revisited
NATALIA STERNBERG, *Clark University*

The formulation of the plasma-wall problem goes back to Langmuir and Tonks, but up to this day has remained an intriguing and controversial problem. Its numerical solution shows a smooth transition from plasma to sheath and provides a limited understanding of the plasma-sheath interface. In many applications (such as plasma probe diagnostics, dc and rf discharges) the electrical properties of bounded plasma-sheath systems are controlled by the sheath. It is therefore common to study plasma and sheath separately using different mathematical models which provide an insight into each region. These models are quite simple, and often can be solved analytically, or by using simple numerical schemes. When plasma and sheath are studied separately, one has to decide how to join the solutions of the corresponding models. Two approaches are found in the literature to deal with this problem: one is the method of matched asymptotic expansions and the second one is patching. Application of asymptotic matching techniques to the plasma-wall problem has led to important theoretical results. However, the mathematical formalism and complexity associated with that method makes it difficult to use in applications. Moreover, the asymptotic plasma and the sheath solutions cannot be matched directly, and the modeling of an intermediate layer between the plasma and the sheath is required for a successful matching. Patching seems to be a more practical approach. Its idea is to join solutions of two different models by forcing their values and perhaps several derivatives to agree at some chosen point (the patching point). The main purpose of patching is to obtain continuity, but, in theory, smoothness is also possible. In contrast to asymptotic matching, it is possible to patch the plasma and the sheath solutions directly, eliminating the need for modeling an intermediate layer. The subject of this presentation is to discuss various fluid plasma and sheath models and their relationship to the corresponding plasma-wall problem. We will discuss the regions where the plasma and the sheath solutions are valid and develop discrete two-media plasma-sheath models which can be used to express the sheath characteristics through the plasma characteristics, or to find the integral characteristics of the sheath for given plasma parameters.

Contributed Papers

8:30
CT1 2 Dust particle charge and screening in the collisional RF plasma sheath JOB BECKERS, DIRK TRIENEKENS, GERRIT KROESEN, *Eindhoven University of Technology* ELEMENTARY PROCESSES IN GAS DISCHARGES TEAM Once immersed in plasma, a dust particle gathers a highly negative charge due to the net collection of free electrons. In most plasma's on earth and with particle sizes is in the micrometer range, the gravitational force is dominant and consequently the particle ends up within the plasma sheath region where it is confined due to balancing gravitational and electrical forces. In the plasma sheath region, the Orbital Motion Limited theory predicts charge values that significantly deviate from reality. This is due electron depletion and due the large directed drift velocity of ions, complexifying the prediction of the particle's charge dramatically. We have developed a novel method to measure the charge of a microparticle (10 μm in diameter and confined in a flat potential well above an RF powered electrode) by studying the horizontal interaction with another particle (equally in size) when the angle of the flat part of the potential well is varied with respect to the earth's horizontal plane. Measured particle charges are within the error bars of earlier measurements of the charge of the same particles and comparable plasma conditions during experiments under hyper-gravity conditions in a centrifuge.

9:00
CT1 4 Investigation of Presheath and Sheath Using a Full-Vlasov Simulation* KENTARO HARA, IAIN BOYD, *University of Michigan* VLADIMIR KOLOBOV, *CFD Research Corporation* A direct simulation method is used to solve the Vlasov equation coupled with collision terms. In comparison to particle simulations, statistical noise is significantly reduced in a direct Vlasov simulation making it attractive for resolution of velocity distribution functions (VDFs) in low-temperature plasmas.† Here, a one-dimensional full-Vlasov simulation is used to investigate the interaction of plasma and a floating wall. Firstly, a collisionless case is considered that assumes a Maxwellian VDF shifted by the Bohm velocity for ions at the sheath edge. The Vlasov solution shows good agreement with the analytic solution. Secondly, by including collisions and applying a quasineutral boundary condition, a smooth transition from presheath to sheath is observed without imposing the Bohm criterion. For a xenon plasma of 5 eV and 10^{15} m^{-3}, the sheath potential is 5.5 T_e/e when the sheath edge is defined as the point where the ion mean velocity equals the ion acoustic velocity. This result agrees with the classical theory that suggests the sheath potential is 5.27 T_e/e. It is also observed that momentum exchange collisions are needed for a converged solution of the presheath-sheath structure.

*Supported by the U.S. Department of Energy Office of Science, Fusion Energy Sciences Program, Grant # DE-SC0001939, and the Air Force Research Laboratory Grant # F9550-09-1-0695.
†V. Kolobov and R. Arslanbekov, J. Comput. Phys., 231, 839 (2012).

9:15
CT1 5 A sheath model for arbitrary radiofrequency waveforms M.M. TURNER, *Dublin City University* PASCAL CHABERT, *LPP, CNRS-Ecole Polytechnique* The sheath is often the most important region of a rf plasma, because discharge impedance, power absorption and ion acceleration are critically affected by the behaviour of the sheath. Consequently, models of the sheath are central to any understanding of the physics of rf plasmas. Lieberman

has supplied an analytical model for a radio-frequency sheath driven by a single frequency, but in recent years interest has been increasing in radio-frequency discharges excited by increasingly complex wave forms. There has been limited success in generalizing the Lieberman model in this direction, because of mathematical complexities. So there is essentially no sheath model available to describe many modern experiments. In this paper we present a new analytical sheath model, based on a simpler mathematical framework than that of Lieberman. For the single frequency case, this model yields scaling laws that are identical in form to those of Lieberman, differing only by numerical coefficients close to one. However, the new model may be straightforwardly solved for arbitrary current waveforms, and may be used to derive scaling laws for such complex waveforms. In this paper, we will describe the model and present some illustrative examples.

SESSION CT2: PLASMA SURFACE INTERACTIONS
Tuesday Morning, 23 October 2012
Room: Classroom 203 at 8:00
Vince Donnelly, University of Houston, presiding

Contributed Papers

8:00
CT2 1 MD simulations of hydrogen plasma interaction with graphene surfaces DAVID GRAVES, *University of California at Berkeley* EMILIE DESPIAU-PUJO, ALEXANDRA DAVYDOVA, GILLES CUNGE, *CNRS/UJF-Grenoble1/CEA LTM* LAURENCE MAGAUD, *CNRS/UJF-Grenoble 1 Institut Néel* Development of graphene-based technologies relies on the capability to grow and integrate this new material into sophisticated devices but the nm-scale control of graphene processing challenges current processing technology. Plasma-graphene interactions must be carefully controlled to avoid damage to the active layers of graphene-based nanoelectronic devices. Pulsed plasmas will minimize surface damage from ions, and help control neutral chemistry, but they must be better understood. We applied molecular dynamics (MD) simulations, coupled with experiments, to better understand and control the plasma-graphene surface interaction. The influence of graphene temperature and incident species energy on adsorption, reflection and penetration mechanisms is presented. Except for impacts at graphene nanoribbon edges or at defects location, H species are shown to experience a repulsive force due to delocalized π-electrons which prevents any species with less than $\sim$ 0.6 eV to adsorb on the graphene surface. Bonding of H to C requires a local rehybridization from sp2 to sp3 resulting in structural changes of the graphene sample. Energetic H+ bombardment of stacked multilayer graphene sheets are analyzed and the possibility to store hydrogen between adjacent layers is discussed.

8:15
CT2 2 Atomic Hydrogen Measurements in a Fusion-Relevant Plasma CAMERON SAMUELL, CORMAC CORR, *Australian National University* PLASMA RESEARCH LABORATORIES TEAM Critical to the success of large-scale fusion reactors is the development of new materials that can withstand the extreme conditions at the plasma-surface boundary. The materials required for plasma-facing components will need to withstand a very aggressive environment that is characterized by both a high heat load and high ion flux produced by the hydrogen isotope plasma. As such, investigating the ways in which hydrogen plasmas interact with a range of materials is an important area for research and development and is vital to the future success of fusion. A new experimental reactor, the MAGnetized Plasma Interaction Experiment (MAGPIE), has been constructed at the Australian National University to help resolve some of the critical issues surrounding the choice of fusion reactor materials. MAGPIE is a linear system with a 2.5 kW, 13.56 MHz helicon source that operates in a magnetic hill configuration with field strengths up to 0.19T. Densities up to $10^{19}m^{-3}$ at temperatures < 5 eV have been achieved. The focus of this presentation is the interaction between a magnetized hydrogen plasma and tungsten and graphite targets in MAGPIE. Results from two-photon absorption laser induced fluorescence (TALIF), optical emission spectroscopy (OES) and probe diagnostics will be presented.

8:30
CT2 3 Comparison of CF_4, CHF_3 and CH_2F_2 plasmas used for wafer processing STEFAN TINCK, *University of Antwerp* ALEXEY MILENIN, *imec Belgium* ANNEMIE BOGAERTS, *University of Antwerp* UNIVERSITY OF ANTWERP COLLABORATION, IMEC BELGIUM COLLABORATION Fluorocarbon-based plasmas are widely used in the microelectronics industry for the fabrication of computer chips, i.e. in plasma etching of silicon. One such process is the etching of nanoscale trenches in the Si substrate with CH_xF_y plasmas as applied in shallow trench isolation (STI). By carefully altering the ratio between gases such as CF_4, CHF_3 and CH_2F_2, the overall etching process can be controlled in terms of chemical etching, sputtering and sidewall passivation. Therefore, we wish to obtain a more fundamental understanding of these plasmas and their surface processes. The plasma behavior will be simulated by a hybrid model for addressing the various plasma species, while the surface interactions of the plasma will be described by additional Monte Carlo simulations, allowing a detailed insight in the nanoscale trench etching process. Bulk plasma properties such as species densities, temperatures and fluxes towards the walls will be discussed under typical wafer processing conditions as well as surface properties including etch rate and chemical composition of the surface during trench etching. The etch rate and microscopic etch profiles will be compared with experimental data.

8:45
CT2 4 Effect of cathode cooling efficiency and oxygen plasma gas pressure on the hafnium cathode wall temperature KOUSTUBH ASHTEKAR, *ABB Inc.* GREGORY DIEHL, JOHN HAMER, *ESAB Welding & Cutting Products* The hafnium cathode is widely used in DC plasma arc cutting (PAC) under an oxygen gas environment to cut iron and iron alloys. The hafnium erosion is always a concern which is controlled by the surface temperature. In this study, the effect of cathode cooling efficiency and oxygen gas pressure on the hafnium surface temperature are quantified. The two layer cathode sheath model is applied on the refractive hafnium surface while oxygen species (O2, O, O+, O++, e-) are considered within the thermal dis-equilibrium regime. The system of non-linear equations comprising of current density balance, heat flux balance at both the cathode surface and the sheath-ionization layer is coupled with the plasma gas composition solver. Using cooling heat flux, gas pressure and current density as inputs; the cathode wall temperature, electron temperature, and sheath voltage drop are calculated. Additionally, contribution of emitted electron current (Je) and ions current (Ji) to the total current flux are estimated. Higher gas pressure usually reduces Ji and increases Je that reduces the surface temperature by thermionic cooling.

9:00

CT2 5 Ultra low-k dielectrics damage under VUV and EUV radiation* SERGEY ZYRYANOV, OLEG BRAGINSKY, ALEXANDER KOVALEV, DMITRY LOPAEV, YURY MANKELEVICH, TATYANA RAKHIMOVA, ALEXANDER RAKHIMOV, ANNA VASILIEVA, *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia* MIKHAIL BAKLANOV, *IMEC, Leuven, Belgium* Low-k dielectric films can be substantially damaged during plasma processing. High energy UV photons emitted by plasma play the key role in damaging the porous low-k films directly or indirectly by stimulating chemical reactions with radicals in plasma. The damage for ultra low-k (ULK, k < 2.2) films with higher porosity and increased pore radius becomes more intense because of the increased penetration depth of UV photons and radicals. Three key wavelength ranges (VUV, DUV and EUV) were studied by exposing the different ULK samples (k: 2.0–2.2, porosity: 30–50%, pore radius: 1–2 nm) to UV radiation at 13.5, 58.3 (mainly effect the Si-O-Si bonds) and 193 nm (mainly effect C-C and C-H bonds) varying the photon dose. ULK damage was studied using FTIR spectroscopy (chemical bond modification), XRF analysis (atom and radical extraction) and ellipsometry (changes in ULK film thickness and dielectric constant).

*This research was supported by SRC Collaboration (Task 2280.001), MSU-IMEC Agreement, RFBR (12-02-00536-a) and Grant MK-6009.2012.2.

9:15

CT2 6 Plasma surface interaction in hot filament cathode arc discharge used to nitride steel substrates R.P. DAHIYA, O. SINGH, V. AGGARWAL, *Centre for Energy Studies, Indian Institute of Technology Delhi, New Delhi - 110016, India* H.K. MALIK, *Department of Physics, Indian Institute of Technology Delhi, New Delhi - 110016, India* NISHA KUMARI, *DBCR University of Science and Technology, Murthal -131039, India* Plasma-assisted nitriding process is a well developed technique for increasing the surface hardness. The process is energy efficient, environment friendly and versatile to treat samples of various shapes and sizes. Though the use of this process in industry is established, there are several scientific questions in the basic understanding of the migration of ions, electrons and radicals and plasma surface interaction. We have studied these processes in an experimental system developed with hot cathode arc discharge plasma. A mixture of nitrogen and hydrogen is utilized for plasma generation. Negatively biased steel substrate is nitrided in this plasma. The hot cathode arc discharge plasma source is utilized to independently monitor and optimise the plasma and the work piece parameters. Substrate bias and temperature, which are the important parameters for achieving the desirable surface hardness, are regulated. Hardness depth profile and nitrogen content in the hardened sample are also measured. Transport and diffusion of ions, electrons, radicals and neutrals are considered to explain the results.

SESSION CT4: MICRODISCHARGES I
Tuesday Morning, 23 October 2012
Room: Salon DE at 8:00
Larry Overzet, University of Texas at Dallas, presiding

Contributed Papers

8:00

CT4 1 Characterisation of a rf micro hollow cathode discharge and its interactions with nearest neighbours SAM DIXON, ROD BOSWELL, CHRISTINE CHARLES, *Australian National University* JOHN HOLLAND, WES COX, *Lam Research Corporation* SPACE PLASMA, POWER AND PROPULSION LABORATORY TEAM, LAM RESEARCH CORPORATION COLLABORATION A novel microplasma hollow cathode plasma source of 4 mm diameter and driven by 13.56 MHz is investigated using 3D sweeps of Langmuir probes in the downstream plasma expansion region. Initial results suggest that the plasma expansion is a simple diffusion from the exit orifice of the 30 mm long cylindrical source region. By making comprehensive measurements of the plasma plumes produced by two micro hollow cathode sources separated by differing distances, the mutual interaction between these components of the system have been determined with the aim of determining whether a much larger array of sources could be envisioned. The effectiveness of the plasma in dissociating reactive species was tested using SF_6 and measuring etch patterns on unbiased silicon wafers. The results have been modeled and show that it is indeed possible to produce a uniform spread of active species over large areas.

8:15

CT4 2 Microhollow Cathode Sustained Discharge with Split Third Electrodes SHARMIN SULTANA, JICHUL SHIN, *University of Ulsan* The characteristics of stable, non-equilibrium, diffuse glow micro-hollow cathode sustained discharge (MCSD) with split third electrodes at moderate to atmospheric pressure in various flow rates are studied experimentally. Enlargement of sustained discharge volume in a split-electrode configuration is about eight times larger than that in a single planar third electrode case. At 100 Torr a maximum expansion of sustained glow discharge is measured as large as 10.3 mm with nine split third electrodes. Analytic estimate of average electron number density at the maximum expansion is measured to be as high as 2.99×10^{10} cm^{-3} at 5 mA third electrode current. In the presence of 0.1 slpm gas flow, the discharge region increases to 18.8 mm with corresponding estimated density of 2.48×10^{10} cm^{-3} at the same third electrode current. For specific pressure ranges, Faraday dark space is clearly visible near the MHCD hole. In the presence of gas flow across the gap, the sustained discharge is affected by linear momentum of the gas flow and its characteristics are altered accordingly such as current distribution over the electrodes. Feasibility of developing a flow velocimetry by using this dynamic phenomenon of MCSD with split electrodes is also studied.

Invited Papers

8:30

CT4 3 Impact of gas heating on an rf-plasma structure in a microcell at high pressure*
TOSHIAKI MAKABE, *Faculty of Science and Technology, Keio University*

In a micro-plasma confined in a small volume at atmospheric pressure, we may have to consider the influence of the local heating of feed gases on the inner plasma parameters, plasma production rate etc. A capacitively coupled micro-plasma in an axisymmetric two dimensional space is theoretically investigated in Ar driven at 13.56 MHz as a typical example. The governing equation of temperature in a gas phase and on a wall is joined with conventional system equations of electrons, ions and long-lived metastable molecules as well as the potential based on the relaxation continuum (rct) model. We first stress in the micro-plasma at atmospheric pressure that an electron with intermediate energy plays an important role in plasma production through stepwise ionization in the presence of high-density metastable having a low ionization threshold. A new sustaining mechanism in the rf-CCP will be demonstrated. That is, the rf micro-plasma is sustained in the instantaneous anode-phase of the powered electrode. Secondly we bring up the enhancement of the net ionization rate by high energy electrons through the increase of the local reduced field, E(r,t)/N(r), under the appearance of a broad minimum of the number density of the heated neutral gas. In the later part of the talk, we will discuss the historically development of the basic concept, reduced-field, employed in the field of collisional low temperature plasmas.

*Work done in collaboration with Masaki Yamasaki and Takashi Yagisawa, Faculty of Science and Technology, Keio University.

Contributed Papers

9:00

CT4 4 Particle-in-Cell Simulations of ns-pulse and RF driven microdischarges* ALEXANDRE LIKHANSKII, *Tech-X Corporation* SERGEY MACHERET, *Lockheed Martin Aeronautics Company* Over past decades, microplasma devices (MPDs) became popular research subject for their unique properties and wide range of applications, such as optical emitters, transistors, electron/ion sources, etc. However, MPD integration into electric circuits for consequent transition into industrial applications requires both reduction of MPD sizes and more detailed understanding of the physics behind its operation. In the presentation, we will demonstrate results of kinetic simulation of the state-of-the-art MPD, developed at UIUC and/or at Lockheed Martin, using Tech-X's code VORPAL. We will investigate the dependences of ignition voltage and relevant plasma parameters (such as EEDF, charge carrier density, etc.) during quasi steady-state MPD operation on gas pressure and applied voltage profile.

*Work supported by DARPA.

9:15

CT4 5 Microwave-Excited Microplasma Thrusters Using Surface Wave and Electron Cyclotron Resonance Discharges DAISUKE MORI, TETSUO KAWANABE, 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 studied two types of microwave-excited microplasma thrusters, using surface wave-excited and electron cyclotron resonance-excited discharges. Microwaves of S-band (4 GHz) and X-band (11 GHz) were employed to excite the plasma in these experiments, with the feed or propellant gases of Ar and He. A microplasma thruster of electrothermal type consisted of a surface wave-excited microplasma source, and a converging-diverging micronozzle to obtain the thrust. For 11-GHz microwaves at a power of 6 W, a thrust of 1.1 mN and a specific impulse of 90 s were obtained at an Ar gas flow rate of 40 sccm, where the plasma electron density was 1.2×10^{20} m^{-3}, and the gas temperature was 1.5×10^{3} K; under the same conditions for 4-GHz microwaves, the thrust, specific impulse, electron density, and gas temperature were 0.93 mN, 80 s, 7.0×10^{19} m^{-3}, and 8.0×10^{2} K, respectively. A microplasma thruster of electromagnetic type had a microplasma source excited by electron cyclotron resonance with external magnetic fields, to obtain the thrust through accelerating ions by ambipolar electric fields. Optical emission spectrum was dominated by Ar^{+} ion lines in the microplasma thruster of electromagnetic type, owing to higher electron temperatures at lower feed-gas pressures.

SESSION DT1: DIAGNOSTICS I
Tuesday Morning, 23 October 2012
Room: Amphitheatre 204 at 10:00
Keiichiro Urabe, University of Tokyo, presiding

Contributed Papers

10:00

DT1 1 Overview of the electric propulsion plasma diagnostics suite for the VASIMR VX-200 testbed CHRISTOPHER OLSEN, BENJAMIN LONGMIER, MAXWELL BALLENGER, JARED SQUIRE, TIM GLOVER, MARK CARTER, *Ad Astra Rocket Company* EDGAR BERING, MATTHEW GIAMBUSSO, *University of Houston* AD ASTRA ROCKET COMPANY/UNIVERSITY OF HOUSTON TEAM Descriptions of the various plasma diagnostics and data analysis methods are given for instruments used in high power (> 100 kW) electric propulsion testing. These include planar Langmuir probes, an articulating retarding potential analyzer, a double Langmuir probe, a multi-axis magnetometer, a high frequency electric field probe, microwave interferometer, and momentum flux targets. These diagnostics have been used to measure the efficiencies of the thruster, plasma source, ion cyclotron resonance booster, and magnetic nozzle as well as used to explore physical phenomena in the plume such as ion/electron detachment, plasma turbulence, and magnetic field line stretching. Typical plume parameters range up to 10^{13} cm^{-3} electron density, 1 kG applied magnetic fields, ion energies in excess of 150 eV, and cold electrons (2–5 eV) with a spatial measurement range over 2 m.

10:15

DT1 2 Elucidating turbulence dynamics with advanced flow and electric field diagnostics in the large-scale, low temperature, EC heated Texas Helimak plasma* W.L. ROWAN, K.W. GENTLE, ALVARO GARCIA DE GORORDO, G.A. HALLOCK, *Institute for Fusion Studies, The University of Texas at Austin* Understanding flow shear is essential to most applications of fluid dynamics in that it generally leads to instability and turbulence in three-dimensional flows. However, in a magnetized plasma – where the equations can often be reduced to two dimensions, shear in the plasma flow velocity transverse to the magnetic field is a very general mechanism for stabilizing turbulence. This theoretical concept is widely invoked, but demonstrations of correlation between flow shear and turbulence suppression in controlled experiments are few. This presentation describes the new research opportunities offered in this area by the The Texas Helimak experiment and its diagnostics. Sharply focused experiments on this novel device require advanced diagnostics. Plasma flow is measured with an imaging spectrometer. More than a hundred Langmuir probes measure turbulence, plasma temperature, plasma density, and electric field. A heavy neutral beam was constructed and is capable of high resolution plasma potential measurements in the plasma. Additional spectroscopic diagnostics are used for supplementary measurement of temperature and density. The data is acquired, stored, and made available within a framework that can be maintained and upgraded by scientists and students.

*Supported by the US DoE.

10:30

DT1 3 The Multiple Resonance Probe: A Novel Device for Industry Compatible Plasma Diagnostics* RALF PETER BRINKMANN, ROBERT STORCH, MARTIN LAPKE, JENS OBERRATH, CHRISTIAN SCHULZ, TIM STYRNOLL, *Ruhr University Bochum* CHRISTIAN ZIETZ, *Leibniz University Hannover* PETER AWAKOWICZ, THOMAS MUSCH, THOMAS MUSSENBROCK, ILONA ROLFES, *Ruhr University Bochum* PLUTO TEAM To be useful for the supervision or control of technical plasmas, a diagnostic method must be i) robust and stable, ii) insensitive to perturbation by the process, iii) itself not perturbing the process, iv) clearly and easily interpretable without the need for calibration, v) compliant with the requirements of process integration, and, last but not least, vi) economical in terms of investment, footprint, and maintenance. Plasma resonance spectroscopy, exploiting the natural ability of plasmas to resonate on or near the electron plasma frequency, provides a good basis for such an "industry compatible" plasma diagnostics. The contribution will describe the general idea of active plasma resonance spectroscopy and introduce a mathematical formalism for its analysis. It will then focus on the novel multipole resonance probe (MRP), where the excited resonances can be classified explicitly and the connection between the probe response and the desired electron density can be cast as a simple formula. The current state of the MRP project will be described, including the experimental characterization of a prototype in comparison with Langmuir probes, and the development of a specialized measurement circuit.

*The authors acknowledge the support by the Federal Ministry of Education and Research in frame of the PluTO project.

10:45

DT1 4 Novel diagnostic tool, curling probe, for monitoring electron density during plasma processing* ANIL PANDEY, KIMITAKA KATO, SHUNJIRO IKEZAWA, KEIJI NAKAMURA, HIDEO SUGAI, *Chubu University* A new type of microwave resonator probe, *curling probe*, has recently been proposed [1] which enables direct measurement of electron density even in plasma deposition process. The FDTD simulation of 10-mm-diam curling probe shows a sharp resonance at the frequency from 1 to 6 GHz uniquely determined by the electron density. The resonance frequencies measured by the curling probe in ICP and microwave plasma were explained well by the FDTD simulation result as well as the analytical formula. When a dielectric layer is deposited on the probe surface, the resonance frequency decreases with the increasing layer thickness. Using this probe characteristic, one can *in situ* monitor the thickness of dielectric layer deposited onto a wall of plasma vessel, where the curling probe is positioned to just the same surface as the inner wall. The FDTD simulation shows ~2 MHz shift in the resonance frequency for deposition of 3-μm-thick dielectric layer, in good agreement with the experimental observation. Thus, the wall deposition layer during chamber cleaning or CVD process can be *in situ* monitored by the curling probe.

*Knowledge Cluster Initiative (second stage), Japan.

[1] I. Liang, K. Nakamura, and H. Sugai, Appl. Phys. Express **4**, 066101 (2011).

11:00

DT1 5 Electrical and optical diagnostics of CO2 microwave plasmas produced by a radial-line slot antenna SE YOUN MOON, DEMETRE J. ECONOMOU, VINCENT M. DONNELLY, *Department of Chemical and Biomolecular Engineering, University of Houston* JIANPING ZHAO, LEE CHEN, RADHA SUNDARARAJAN, YOSHIO SUSA, TOSHIHISA NOZAWA, *Tokyo Electron America* CO2 plasmas generated by microwave power supplied to a radial-line slot antenna were studied by Langmuir probe and optical spectroscopic methods. At a distance of 190 mm from the slot antenna, the electron temperature and electron density were 2.4 eV and 8.5E10 cm^{-3}, respectively, at 10 mTorr with 3 kW microwave power. At a pressure of 150 mTorr, the electron temperature decreased to below 1 eV while the electron density dropped to 8.6E9 cm^{-3} because the plasma was then localized near the antenna. Low electron temperature is advantageous for reducing some forms of device damage. In addition, the gas temperature, obtained from the rovibrational spectra of added N2 gas, increased from 650 K at 10 mTorr to 1160 K at 50 mTorr. Further increase in gas pressure up to 150 mTorr resulted in a slight decrease of the gas temperature, again due to plasma localization near the antenna. The atomic oxygen density, derived using actinometry, was 5.7E1012 cm^{-3} at 10mTorr and 5.6E13 cm^{-3} at 150 mTorr with 3kW. Results using trace rare gas optical emission spectroscopy (TRG-OES) and vacuum ultra-violet absorption spectroscopy will also be presented and compared with Langmuir probe measurements and actinometry.

11:15

DT1 6 Langmuir probes in the intense rf environment inside a helicon discharge FRANCIS F. CHEN, *UCLA* High-density helicon discharges are usually studied downstream from the antenna region. Langmuir probes are hard to use there because of the intense rf environment and heavy bombardment by ions and electrons. The plasma studied here is a small helicon discharge with permanent magnets to provide the dc B-field. A very thin probe was designed for the small discharge (5 cm diam × 5 cm long) without disturbing it. A floating rf-compensation electrode (CE) supplemented the self-resonant chokes to filter out the rf pickup of 30-50V peak-to-peak. The effect of CE size is shown. Saturation ion current varies with the square root of probe potential V_p well beyond to expected validity range of the Langmuir Orbital Motion Limited formula. Fitting the $I^2 - V$ curve with a straight line, we subtract the fitted ion current from total current to obtain the $\ln(I_e) - V_p$ curve. This is almost always straight, indicating Maxwellian electrons. With high B-fields and collisions, the transition region of the $I - V$ characteristic is very short, and sometimes absent. However, T_e can be obtained correctly in the ion-subtraction region. This is fortunate, since drawing saturation electron current can drive the probe to emission. Interesting effects of electron emission will be shown.

11:30

DT1 7 Electron Energy Distribution Function Measurements in a Negative Hydrogen Ion Source* JOHN BLANDINO, ZACHARY TAILLEFER, *Worcester Polytechnic Institute* LYNN OLSON, *Busek Co. Inc.* A High Pressure Discharge Negative Ion Source (HPDNIS) operating on hydrogen has been built and tested. The HPDNIS uses an RF discharge operating in a pressure range of 10s to 100s of Torr. Gas from this discharge flows through an orifice into a lower pressure (10s of mTorr), negative ion production region designed to maintain low electron temperature and enhance negative ion formation through dissociative attachment. Plasma exiting the negative ion production region is extracted through a biased grid set with separation of negative ions and electrons achieved via an applied magnetic field. This presentation will describe measurements of the electron energy distribution function (EEDF), in the negative ion production region, made using a single Langmuir probe based on the Druyvesteyn method. The presentation will discuss challenges to using this method as a result of complications arising from the presence of negative ion species, collisionality, and RF induced distortion of the EEDF. The presentation will also summarize estimates of the rate constant for collisional processes such as dissociative attachment, made using the measured EEDFs in the negative ion production region of the HPDNIS.

*This work supported by the Department of Energy.

11:45

DT1 8 Langmuir Probe RF Plasma Compensation using Simulation Method AASIM YOUSIF AZOOZ, *Professor* The problem Langmuir probe data deformation due to RF pickup by the probe is treated through computer simulation method. It is pointed out that proper RF effects compensations can be obtained by proper software treatment of the RF contaminated data. It is demonstrated that correct RF unaffected probe I-V characteristics can be accurately reproduced from the RF contaminated data. This eliminates the need for the use of any filters or other hardware procedures. User friendly matlab based software is presented. The software automatically retrieves the correct RF unaffected I-V characteristics for single and double Langmuir probe data which consequently allows for proper evaluation of plasma parameters such as the plasma electron temperature, electron number density and the electron energy distribution function (EEDF).

12:00

DT1 9 On multiple component detection in molecular plasmas using cw external-cavity quantum cascade infrared lasers DMITRY LOPATIK, NORBERT LANG, UWE MACHERIUS, HENRIK ZIMMERMANN, JUERGEN ROEPCKE, *INP Greifswald, Greifswald, Germany* Several cw external cavity quantum cascade lasers (EC-QCLs) have been tested as radiation sources for an absorption spectrometer focused on the analysis of molecular plasmas. Based on the wide spectral tunability of EC-QCLs multiple species detection is demonstrated in low pressure Ar/N_2 MW plasmas containing CH_4 as hydrocarbon precursor. Using the direct absorption technique the evolution of the concentrations of CH_4, C_2H_2, HCN and H_2O has been monitored depending on the discharge conditions (p = 0.5 mbar, f = 2.45 GHz) in a planar MW plasma reactor. The concentrations were found to be in the range of 10^{11}–10^{14} molecules cm^{-3}. Based on the profiles of absorption lines the gas temperature T_g has been calculated in dependence on the discharge power. Changing the discharge power from 0.2 kW to 1 kW leads to an increase of T_g from 400 to 700 K. The typical spectral line width of the EC-QCLs under the study was about 30 MHz. Varying the power values of an EC-QCL for direct absorption measurements at low pressure conditions no saturation effects in determining the concentrations of CH_4 and C_2H_2 could be found under the used conditions.

SESSION DT2: LOW PRESSURE PLASMA SOURCES
Tuesday Morning, 23 October 2012
Room: Classroom 203 at 10:00
Prashanth Kothnur, Applied Materials Inc., presiding

Contributed Papers

10:00

DT2 1 Two-Dimensional Electron and Metastable Density Profiles Produced in Helium Fast Ionization Wave Discharges* BRANDON WEATHERFORD, EDWARD BARNAT, *Sandia National Laboratories* ZHONGMIN XIONG, MARK KUSHNER, *University of Michigan* Fast ionization wave (FIW) discharges are those in which nanosecond-duration pulses at high overvoltage are used to initiate large volume breakdown at elevated pressures. This presentation summarizes recent studies of spatial distributions of electron and metastable production in a helium FIW discharge. Two-dimensional laser collision-induced fluorescence (2D-LCIF) is used to generate spatially and temporally resolved maps of electron and metastable densities produced by a FIW with positive polarity pulses of >10 kV, with 20 ns duration and ~3 ns rise time. The results show that radial profiles depend strongly on operating pressure (1-20 Torr) and pulse repetition rate (0.2-2 kHz); these trends are discussed and correlated with measured FIW propagation velocities and estimates of the effective reduced electric field (E/N) in the FIW wavefront. Differences between the electron and metastable profiles are related to the uniformity of energy deposition in FIWs. Results from a two-dimensional computational model are presented, which capture similar trends as those seen in experiment. A comparison between experimental and modeling results is discussed to provide additional insights into the physical processes behind FIW propagation.

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

10:15

DT2 2 A Plasma Based OES-CRDS Dual-mode Portable Spectrometer for Trace Element Detection: Emission and Ringdown Measurements of Mercury* PEEYUSH SAHAY, SUSAN SCHERRER, CHUJI WANG, *Mississippi State University* LASER SPECTROSCOPY AND PLASMA TEAM Design and development of a plasma based optical emission spectroscopy-cavity ringdown spectroscopy (OES-CRDS) dual-mode portable spectrometer for *in situ* monitoring of trace elements is described. A microwave plasma torch (MPT) has been utilized, which serves both as an atomization and excitation source for the two modes, viz. OES and CRDS, of the spectrometer. Operation of both modes of the instrument is demonstrated with initial measurements of elemental mercury (Hg). A detection limit of 44 ng mL^{-1} for Hg at 253.65 nm was determined with the emission mode of the instrument. Severe radiation trapping of 253.65 nm line hampers the measurement of Hg in higher concentration region (> 50 μg ml^{-1}). Therefore, a different wavelength, 365.01 nm, is suggested to measure Hg in that region. Ringdown measurements of the metastable 6s6p $^3P_0$ state of Hg in the plasma using a 404.65 nm palm size diode laser was conducted to demonstrate the CRDS mode of the instrument. Along with being portable, dual-mode, and self-calibrated, the instrument is capable of measuring a wide range of concentration ranging from sub ng mL^{-1} to several μg ml^{-1} for a number of elements.

*This work is supported by the US Department of Energy grant DEFC01006EW07040 and the National Science Foundation grant No. CBET-1066486.

10:30

DT2 3 Relaxation of High Power Microwave Surface Plasma* STERLING BEESON, ANDREAS NEUBER, *Center for Pulsed Power and Power Electronics, TTU* The electron loss mechanisms related to the relaxation of pulsed rf-generated plasma are investigated. A 3 MW, 3 μs width, 50 ns risetime high power microwave pulse is transmitted through a dielectric window that terminates a WR-284 (S-band) waveguide filled with insulating gas where the investigated plasma is formed across this window on the atmospheric side. This produces electron densities on the order of 10^{14} cm^{-3} for pressures of 10 to 400 torr in air, N_2 and argon environments. This plasma attenuates the pulse on the order of -40 to -10 dB during peak electric field amplitudes. Using a multi-standard waveguide coupler to inject a low power probing signal, the post-pulse attenuation values are measured and used to quantify the temporal evolution of the electron density. This technique is confirmed by means of verifying the attachment rates in an air environment and 2-body recombination rate in a N_2 environment. The major recombination processes for high pressure argon plasma are identified, e.g. 3-body recombination becomes dominant within the first few microseconds after pulse termination. The measured rates for recombination are compared with sparsely available data and models from literature in the regime of interest.

*Research supported by an AFOSR Grant on the Basic Physics of Distributed Plasma Discharges along with a SMART student fellowship supported by the U.S. Army.

10:45

DT2 4 Fundamental TE_{11} Mode and Plasma Interaction in a Cylindrical Waveguide SANJAY K. TOMAR, HITENDRA K. MALIK, *Indian Institute of Technology Delhi* Microwave and plasma interaction has got applications in charged particle acceleration, travelling wave tube amplifiers, gyrotrons, etc. During the propagation of the microwave in a waveguide, it is seen that its wavelength gets larger if the plasma is filled in the waveguide, and also the field of the microwave gets altered. In addition, the plasma density distribution is modified. In the present work, we simulate the problem of this type of interaction by considering the fundamental TE_{11} mode and the plasma filled cylindrical waveguide. We assume that the fundamental mode encounters the plasma in another cylindrical waveguide of the same size. We derive a wave equation using Maxwell's equations for the microwave field along with the contribution of plasma and solve this by using fourth-order Runge-Kutta method. Then the perturbed density is studied in greater detail for the different profiles of the plasma density. The effect of electron temperature, waveguide radius, microwave field and its frequency are studied on the perturbed density that takes the form of bunches.

11:00

DT2 5 A first step toward the modeling of instabilities in high power pulse magnetron sputtering plasmas* SARA GALLIAN, DENIS EREMIN, TORBEN HEMKE, THOMAS MUSSENBROCK, RALF PETER BRINKMANN, *Ruhr University Bochum* WILLIAM N.G. HITCHON, *University of Wisconsin Madison* High Power Pulsed Magnetron Sputtering (HPPMS) is a novel Ionized Physical Vapor Deposition (IPVD) technique, able to achieve an ultra dense plasma with a high ionization degree among the sputtered atoms. This is accomplished by applying a large bias voltage to the target in short pulses with low duty cycle. Several authors have recently reported the presence of rotating structures during a HPPMS discharge. According to the experimental observations, these emissions peaks rotate with constant angular velocity Ω, when the discharge parameters are held constant. Here, we attempt to describe these structures with a collection of simplified models with increasing levels of detail. We start by solving analytically a system of 1D Advection-Diffusion-Reaction equations for the electron $n_e(\theta, t)$ and neutral $n_n(\theta, t)$ densities. Then, we focus on the secondary electron behavior and follow the evolution of their energy. In the light of previous results, we develop a time dependent global model for the ionization region. We solve self-consistently the rate equations for background gas and metal species. The secondary electrons are responsible for the main inelastic collision processes and are therefore treated in detail, kinetically.

*The authors gratefully acknowledge funding by the Deutsche Forschungsgemeinschaft within the frame of SFB-TR 87.

11:15

DT2 6 MAGPIE: A new linear plasma device for studying fusion relevant plasma-surface interactions* CORMAC CORR, CAMERON SAMUELL, BOYD BLACKWELL, JOHN HOWARD, JUAN CANESES, ROMANA LESTER, *Australian National University* AUSTRALIAN NATIONAL UNIVERSITY TEAM Plasma-surface interactions are crucial to determining the success of ITER and the ultimate viability of generating fusion power under steady state conditions. The first walls of magnetic fusion reactors must sustain large particle and heat fluxes and present a major challenge to achieving fusion power. To answer fundamental questions about the science of plasma-surface interactions at the complex fusion boundary a new purpose-built linear plasma device, the prototype MAGnetized Plasma Interaction Experiment (MAGPIE), has been constructed at The Australian National University (ANU) to develop novel diagnostics and test materials under aggressive plasma conditions. In this work we employ optical emission spectroscopy, electrostatic probes and fast imaging to characterize the plasma environment and its interaction with various materials. It will be shown that a well-collimated plasma is created in the downstream region with a diameter of about 2 cm. High-energy electrons are observed along the axis of the discharge and the power deposition region is transferred to where the magnetic field maximum occurs in the downstream region. These findings indicate that efficient non-collisional heating occurs downstream of the plasma source.

*Author CC would like to acknowledge support from the Australian Research Council through a Future Fellowship (FT100100825).

11:30

DT2 7 Two-Dimensional Particle-in-Cell Simulation of Cylindrical Magnetron Sputters for the Improvement of Target Utilization* MIN YOUNG HUR, HYOWON BAE, IN CHEOL SONG, HO-JUN LEE, HAE JUNE LEE, *Pusan National University* PNU PLASMA RESEARCH CENTER TEAM Magnetron sputtering has been commonly used for the deposition of a wide range of industrial thin film coating. This method has almost no restrictions in the target materials and the magnetic field enables lower pressures operation. Conventional flat type sputters generate ion-bombardment sputtering in only a localized region of target where electric fields and magnetic fields are perpendicular to each other. Therefore, the utilization efficiency of the target material is about 20~30%. To overcome this drawback, a rotating cylindrical target is devised to make uniform sputtering on the target. In this paper, the difference of the physical effects of ions on the targets between the flat-type and the cylindrical-type sputters is investigated using a two-dimensional particle-in-cell (PIC) simulation with Monte Carlo collisions. Especially for the calculation of cylindrical field solver with a finite difference method, an image charge method is introduced instead of solving the Poisson equation directly. Simulation Diagnostics include the plasma density, the distributions of energy and angle of incident ions on the target, and the deposition profiles on the substrate calculated by a ray-trace particle deposition model. The analysis for the rotating speed and the magnet structure is

*This work was supported by "Development Program of Nano Process Equipments" of Korea Ministry of Knowledge Economy.

11:45

DT2 8 Simulations of magnetically enhanced capacitively coupled plasma discharges using CFD-ACE+ ANANTH BHOJ, MUSTAFA MEGAHED, *ESI US R&D Inc* VLADIMIR KUDRIAVTSEV, *Intevac* Many plasma processing reactors employ strong magnetic fields to confine or otherwise manipulate the discharge to optimize wafer surface processing [1]. The multi-physics modeling platform CFD-ACE+ was extended to account for the presence of strong magnetic fields on plasma transport in the chamber. The transport coefficients for electrons assume tensor forms whose components are dependent on those of the applied magnetic field. The capacitively coupled plasma (CCP) model either accepts an externally computed magnetic field supplied via user subroutines or uses the solution computed within the magnetic module that addresses the magnetic vector potential equation. In this work, latter approach has been applied to model an Ar discharge in axisymmetric magnetically enhanced CCP reactor configuration. Parametric results over a range of pressures demonstrated the effect of the magnetic field on changing discharge uniformity and plasma density.

[1]http://meetings.aps.org/Meeting/GEC09/Event/107279.

SESSION DT3: GREEN PLASMA TECHNOLOGIES

Tuesday Morning, 23 October 2012; Room: Classroom 202 at 10:00; Walter Lempert, Ohio State University, presiding

Invited Papers

10:00

DT3 1 Modeling of Plasma Assisted Combustion*

HARUAKI AKASHI, *National Defense Academy*

Recently, many experimental study of plasma-assisted combustion has been done. However, numerous complex reactions in combustion of hydrocarbons are preventing from theoritical study for clarifying inside the plasma-assisted combustion, and the effect of plasma-assist is still not understood. Shinohara and Sasaki [1,2] have reported that the shortening of flame length by irradiating microwave without increase of gas temperature. And they also reported that the same phenomena would occur when applying dielectric barrier discharges to the flame using simple hydrocarbon, methane. It is suggested that these phenomena may result by the electron heating. To clarify this phenomena, electron behavior under microwave and DBD was examined. For the first step of DBD plasma-assisted combustion simulation, electron Monte Carlo simulation in methane, oxygen and argon mixture gas (0.05:0.14:0.81) [2] has been done. Electron swarm parameters are sampled and electron energy distribution function (EEDF)s are also determined. In the combustion, gas temperature is higher (>1700K), so reduced electric field E/N becomes relatively high (>10V/cm/Torr). The electrons are accelerated to around 14 eV. This result agree with the optical emission from argon obtained by the experiment of reference [2]. Dissociation frequency of methane and oxygens are obtained in high. This might be one of the effect of plasma-assist. And it is suggested that the electrons should be high enough to dissociate methane, but plasma is not needed.

*This work was supported by KAKENHI(22340170).

[1]K. Shinohara *et al.*, J. Phys. D: Appl. Phys. **42**, 182008 (1-7) (2009).
[2]K. Sasaki, 64th Annual Gaseous Electronic Conference, **56**, 15 CT3.00001 (2011).

Contributed Papers

10:30

DT3 2 A novel microwave plasma combustor toward understanding plasma assisted ignition and plasma assisted combustion of methane/air mixtures* CHUJI WANG, WEI WU, *Mississippi State University* LASER SPECTROSCOPY AND PLASMA TEAM A novel microwave plasma combustor has been developed to study mechanisms of plasma-assisted ignition (PAI) and plasma-assisted combustion (PAC). The system allows us to inject a 2.45 MHz atmospheric argon microwave plasma jet directly into a combustion reaction zone to investigate effects of PAI and PAC. Three distinct zones: a pure plasma zone, a plasma-combustion hybrid zone, and a combustion zone are investigated by optical emission spectroscopy (OES) and cavity ringdown spectroscopy (CRDS) of OH, etc. plasma and combustion intermediates. The experimental results allow us to understand the formation of OH radicals and roles of OH in PAI and PAC of methane-air mixtures in a wide range of fuel equivalence ratios ranging from rich to lean burn. A U-curve of plasma power versus fuel equivalence ratio in the PAI of methane-air mixtures is observed. The roles of OH in PAI and PAC of premixed methane-air flames around the flammability limit are discussed.

*This work is supported by the National Science Foundation through the grant No. CBET-1066486.

10:45

DT3 3 Measurement of OH radical density in dielectric barrier discharge enhanced premixed burner flame KAZUNORI ZAIMA, KOICHI SASAKI, *Hokkaido University* In this work, we examined temporal variation of OH radical density in a premixed burner flame assisted by dielectric barrier discharge (DBD) using cavity-ringdown absorption spectroscopy. We attached a premixed burner to a dielectric base plate, and the upper part of the premixed burner flame with $CH_4/O_2/Ar$ gas mixture was covered with a quartz tube. An aluminum electrode was attached on the outside of the quartz tube, and it was connected to a high-voltage power supply. DBD inside the quartz tube was obtained between the aluminum electrode and the electrically-grounded burner nozzle. To measure the temporal variation of OH radical density, we constructed a system of cavity-ringdown absorption spectroscopy using a cw diode laser. We obtained the absorbance of OH radicals with and without DBD by comparing the ringdown signals observed at an absorption wavelength of OH radicals (6900.690 cm^{-1}) and an off-tuned wavelength (6900.900 cm^{-1}). As a result, it was observed that the density of OH radicals in the presence of DBD was lower than that in the absence of DBD at almost all the discharge phases. It is suggested from the result that the consumption of OH radicals is enhanced due to the change in combustion reactions in the flame in the presence of DBD.

11:00

DT3 4 Surface treatment of dye-sensitized solar cell using dielectric barrier discharge RYO ONO, SHUNGO ZEN, YOSHIYUKI TERAMOTO, KEISUKE HANAWA, SOICHI KOBAYASHI, TETSUJI ODA, *The University of Tokyo* We have developed surface treatment of dye-sensitized solar cell (DSSC) using dielectric barrier discharge (DBD). The DSSC consists of TiO_2 nanoporous photoelectrode sensitized with dye. The photoelectrode is a 10-μm thick film made by sintering TiO_2 paste on a conductive glass substrate at 450 C. After the sintering, the TiO_2 film is dipped into dye solution for sensitization. The DBD treatment is applied to the TiO_2 film after the sintering. The DBD treatment improves the energy conversion efficiency, η, by a factor of 1.05 to 1.15 depending on humidity and O_2 concentration. It can be deduced that radicals such as O, O_3, and OH contribute to the DBD treatment. The DBD treatment also has an effect of reducing the sintering temperature of TiO_2 paste. If the TiO_2 paste is sintered at much lower than 450 C (i.e. $\leqslant$ 300 C), a solar cell cannot be produced, that is, $\eta = 0\%$. However, if the DBD treatment is applied after the low temperature sintering, a solar cell can be produced. This is important because the low-temperature sintering enables us to use materials that cannot resist high temperature. The DBD treatment is also applied to a plastic substrate DSSC. But the DBD causes damage on the TiO_2 film and at present it is not suceeded.

11:15

DT3 5 CO_2 Dissociation by Low Current Gliding Discharge in the Reverse Vortex Flow ALEXANDER GUTSOL, *Chevron Energy Technology Company* If performed with high energy efficiency, plasma-chemical dissociation of carbon dioxide can be a way of converting and storing energy when there is an excess of electric energy, for example generated by solar elements of wind turbines. CO_2 dissociation with efficiency of up to 90% was reported earlier for low pressure microwave discharge in supersonic flow. A new plasma-chemical system uses a low current gliding discharge in the reverse vortex flow of plasma gas. The system is a development of the Gliding Arc in Tornado reactor. The system was used to study dissociation of CO_2 in wide ranges of the following experimental parameters: reactor pressure (15–150 kPa), discharge current (50–500 mA), gas flow rate (3–30 liters per minute), and electrode gap length (1–10 cm). Additionally, the effect of thermal energy recuperation on CO_2 dissociation efficiency was tested. Plasma chemical efficiency of CO_2 dissociation is very low (about 3%) in a short discharge at low pressures (about 15 kPa) when it is defined by electronic excitation. The highest efficiency (above 40%) was reached at pressures 50–70 kPa in a long discharge with thermal energy recuperation. It means that the process is controlled by thermal dissociation with subsequent effective quenching. Plasma chemical efficiency was determined from the data of chromatographic analysis and oscilloscope electric power integration, and also was checked calorimetrically by the thermal balance of the system.

11:30

DT3 6 Numerical simulations for plasma-based dry reforming RAMSES SNOECKX, ROBBY AERTS, ANNEMIE BOGAERTS, *University of Antwerp* The conversion of greenhouse gases (CO2 and CH4) to more valuable chemicals is one of the challenges of the 21st century. The aim of this study is to describe the plasma chemistry occurring in a DBD for the dry reforming of CO2/CH4 mixtures, via numerical simulations. For this purpose we apply the 0D simulation code "Global_kin," developed by Kushner, in order to simulate the reaction chemistry and the actual reaction conditions for a DBD, including the occurrence of streamers. For the chemistry part, we include a chemistry set consisting of 62 species taking part in 530 reactions. First we describe the reaction chemistry during one streamer, by simulating one discharge pulse and its afterglow, to obtain a better understanding of the reaction kinetics. Subsequently, we expand these results to real time scale simulations, i.e., 1 to 10 seconds, where we analyze the effects of the multiple discharges (streamers) and input energy on the conversion and the selectivity of the reaction products, as well as on the energy efficiency of the process. The model is validated based on experimental data from literature.

11:45

DT3 7 Atmospheric Pressure Glow Discharge for Point-of-Use Water Treatment ALEXANDER LINDSAY, BRANDON BYRNS, STEVEN SHANNON, DETLEF KNAPPE, *North Carolina State University* Treatment of biological and chemical contaminants is an area of growing global interest where atmospheric pressure plasmas can make a significant contribution. Addressing key challenges of volume processing and operational cost, a large volume 162 MHz coaxial air-plasma source has been developed.* Because of VHF ballasting effects, the electric discharge is maintained at a steady glow, allowing formation of critical non-equilibrium chemistry. High densities, $n_e = 10^{11}$-10^{12}, have been recorded. The atmospheric nature of the device permits straightforward and efficient treatment of water samples. [H^+] concentrations in 150 milliliter tap water samples have been shown to increase by 10^5 after five minutes of discharge exposure. Recent literature has demonstrated that increasing acidity is strongly correlated with a solution's ability to deactivate microbial contaminants.† The work presented here will explore the impact of treatment gas, system configuration, and power density on water disinfection and PFC abatement. An array of plasma diagnostics, including OES and electrical measurements, are combined with post-process water analysis, including GC-MS and QT analysis of coliform and E. coli bacteria. Development of volume processing atmospheric plasma disinfection methods offers promise for point-of-use treatments in developing areas of the world, potentially supplementing or replacing supply and weather-dependent disinfection methods.

*Byrns (2012) J. Phys. D: Appl. Phys. 45 (2012) 195204
†Traylor (2011) J. Phys. D: Appl. Phys. 44 (2011) 472001

SESSION DT4: CAPACITIVELY COUPLED PLASMAS
Tuesday Morning, 23 October 2012
Room: Salon DE at 10:00
Pascal Chabert, Ecole Polytechnique - CNRS, presiding

Contributed Papers

10:00

DT4 1 Plasma characteristics in non-sinusoidally excited CCP discharges TREVOR LAFLEUR, JEAN-PAUL BOOTH, *LPP Ecole Polytechnique* Using particle-in-cell (PIC) simulations we perform a characterization of the plasma response to positive pulse-type voltage excitations (with a repetition frequency of 13.56 MHz) in a geometrically symmetric CCP reactor (with a gap length of 2 cm) operated with argon (for pressures between 20-500 mTorr). Use of these non-sinusoidal waveforms generates an electrical asymmetry effect in the system, which necessitates the formation of a DC bias. This DC bias, together with the shape of the voltage waveforms used, produces a number of new phenomena that are not present in typical sinusoidal discharges: (1) the plasma density and ion flux can be increased as the pulse width is reduced, (2) a significant asymmetry in the ion fluxes to the powered and grounded electrodes develops as the pressure increases, (3) the average ion energy striking the grounded electrode remains low and approximately constant as the pulse width decreases, and (4) the sheath at the grounded electrode never fully collapses; electrons are no longer lost in sharp pulses, but escape essentially throughout the rf cycle. Effects (1) and (3) above offer the possibility for a new form of control in these types of discharges, where the ion flux can be increased while the ion energy on the grounded electrode can be kept small and essentially constant. This effect has recently been exploited to control the crystallinity of silicon thin films [1], where the low ion bombarding energy was found to improve the quality of films grown.

[1]Johnson E V, Pouliquen S, Delattre P A, and Booth J P, J. Non-Cryst. Solids 2012, in press.

10:15

DT4 2 Tailored Voltage Waveform Capacitively-Coupled Plasmas* JEAN-PAUL BOOTH, TREVOR LAFLEUR, PIERRE-ALEXANDRE DELATTRE, *LPP-CNRS, Ecole Polytechnique, France* ERIK JOHNSON, *PICM-CNRS, Ecole Polytechnique, France* A major limitation of large-area capacitively-coupled plasmas for materials processing is the inability to increase plasma density without increasing ion bombardment energy. Heil *et al.* (J. Phys. D 41, 165202 (2008)) demonstrated that for a driving voltage comprising one frequency, f, and it's harmonic 2f, the symmetry of the sheaths can be broken (the Electrical Asymmetry Effect, EAE). We have investigated large-area plasmas (50cm dia) in Ar driven by arbitrary voltage waveforms. Specifically we studied waveforms comprising sharp positive pulses (10-20ns wide, 15MHz repetition frequency). The voltage waveform was measured by an HV probe close to the powered electrode edge, the electron density was measured with a microwave hairpin resonator, the ion flux was measured by an array of planar ion flux probes in the grounded counter-electrode, and the power absorbed was determined from the current and voltage waveforms measured by a derivative probe. As well as the expected EAE observed in the electrode self-bias, we were able to demonstrate a dramatic increase in electron density (and concomitant increased power absorption) with reduced pulse-width at constant amplitude, in qualitative agreement with recent PIC simulations (Lafleur *et al.*, APL 100, 194101(2012)).

*Supported by ANR-10-HABISOL-002 project CANASTA.

10:30

DT4 3 A numerical analysis of plasma non-uniformity in the parallel plate VHF-CCP and the comparison among various model IKUO SAWADA, *Tokyo Electron US Holdings Inc.* We measured the radial distribution of electron density in a 200 mm parallel plate CCP and compared it with results from numerical simulations. The experiments were conducted with pure Ar gas with pressures ranging from 15 to 100 mTorr and 60 MHz applied at the top electrode with powers from 500 to 2000W. The measured electron profile is peaked in the center, and the relative non-uniformity is higher at 100 mTorr than at 15 mTorr. We compare the experimental results with simulations with both HPEM and Monte-Carlo/PIC codes. In HPEM simulations, we used either fluid or electron Monte-Carlo module, and the Poisson or the Electromagnetic solver. None of the models were able to duplicate the experimental results quantitatively. However, HPEM with the electron Monte-Carlo module and PIC qualitatively matched the experimental results. We will discuss the results from these models and how they illuminate the mechanism of enhanced electron central peak.

[1]T. Oshita, M. Matsukuma, S. Y. Kang, and I. Sawada: *The effect of non-uniform RF voltage in a CCP discharge*, The 57th JSAP Spring Meeting 2010.

[2]I. Sawada, K. Matsuzaki, S. Y. Kang, T. Ohshita, M. Kawakami, and S. Segawa: 1-st IC-PLANTS, 2008.

10:45

DT4 4 Extension of CCP DC Self Bias Models To The Case of Fractional Diversion of Powered Electrode Current to Ground D.L. KEIL, E. AUGUSTYNIAK, E. DORAI, F. GALLI, *Lam Research Corp.* In many commercial CCP plasma process systems the DC-self bias is available as a reported process parameter. Since commercial systems typically limit the number of onboard diagnostics, there is great incentive to understand how DC-self bias can be expected to respond to various system perturbations. This work examines the effect on DC-self bias due "bleeding" DC current to ground through an RF filter and resistor. By extending the work of Y. P. Song *et al.* [1] a relationship between this bleed current and DC bias is developed that predicts DC-self bias change in terms of electrode areas and the Bohm currents to each electrode. Additionally, a circuit model is also presented which gives similar results. These models are then compared to experimental results, with model fit values providing an experimental measure of electrode areas and Bohm currents.

[1]Y. P. Song, D. Field, and D. F. Klemperer, J. Phys. D Appl. Phys **23**, 673 (1990).

11:00

DT4 5 Analysis of the phase controlled capacitively coupled plasma using triode circuit model* MYUNG-SUN CHOI, SEOK-HWAN LEE, GON-HO KIM, *Department of Energy System (Nuclear) Engineering, Seoul National University* DOUGYONG SUNG, *Mechatronics and Manufacturing Technology Center, Samsung Electronics Co. Ltd.* Phase controlled CCP source is attracted recently for high density capacitively coupled VHF plasma source to enhance their poor plasma uniformity due to standing wave effect by controlling phase difference. And it also enhances process performance. But the phase controlled CCP has hardness of controlling plasma density due to the asymmetry of the curve for plasma density with changing phase and its non-linear drift. To understand these characteristics of phase controlled CCP, this work investigates the effect of wall electrode using triode circuit model and compares with experimental results in 100MHz phase controlled CCP source. Plasma density varies with changing ratio of current flowing through the chamber wall and current flowing between electrodes. The asymmetry of the curve for plasma density with phase is due to the effect of area difference of powered electrodes, and this asymmetry increases with the current flowing through the wall electrode. we are going to report the asymmetry effect of electrodes on the plasma density control of phase controlled CCP and discuss the difference of physical area ratio and effective area ratio of triode CCP source.

*This work supported by Samsung Electronics Co. Ltd.

11:15

DT4 6 The effect of the driving frequencies on the Electrical Asymmetry Effect in dual-frequency capacitive radio frequency plasmas JULIAN SCHULZE, *Ruhr-University Bochum* IHOR KOROLOV, *Hungarian Academy of Sciences* UWE CZARNETZKI, *Ruhr-University Bochum* ZOLTAN DONKO, *Hungarian Academy of Sciences* In capacitive radio frequency discharges driven by two consecutive phase locked harmonics, an electrical asymmetry is induced and a DC self bias is generated as a function of the phase shift between the driving frequencies. Until now, only dual-frequency discharges operated at a fundamental frequency of 13.56 MHz have been investigated. It was shown, that a maximum self bias of 25% of the driving voltage amplitude can be generated electrically and that the mean ion energy at the electrodes can be controlled separately from the ion flux by adjusting the phase in a geometrically symmetric reactor. Here, we study the effect of changing this fundamental frequency between 0.5 MHz and 27.12 MHz on the Electrical Asymmetry Effect by Particle-in-Cell simulations and an analytical model for different γ-coefficients. We find the electrical generation of the DC self bias and the quality of the separate control of ion properties to be strongly reduced at lower frequencies. This is caused by the effect of the driving frequencies on the charge and electron heating dynamics. These effects are understood by the model.

11:30

DT4 7 Electromagnetic Particle-in-Cell Simulation of Large Area High-Frequency Capacitive Coupled Plasmas for the Reduction of Standing Wave Effects* JIN SEOK KIM, IN CHEOL SONG, SEOK WON HWANG, HO-JUN LEE, HAE JUNE LEE, *Pusan National University* PNU PLASMA RESEARCH CENTER TEAM A finite difference time domain (FDTD) method was adopted to investigate the electric-field distributions depending on the driving frequency of a 450-mm Capacitive Coupled Plasma (CCP) reactor. High frequency wave contains a short wavelength which induces standing wave effects in the CCP reactor. The induced standing waves make non-uniform electric field distributions which causes bad effects on the uniformity of plasma processing. This presentation shows the plasma density uniformity depending on electrode structures and other factors. The investigation of standing wave effect is coupled with the electromagnetic particle-in-cell (PIC) simulation. A PIC simulation shows very high accuracy compared with fluid simulations and gives more information for electron and ion energy distributions, but has a disadvantage of slow speed caused by individual calculation of lots of computational particles. A computation method using graphic processing units makes it possible to establish a low-cost and low-power personal super computer. In order to overcome the heavy computation problem of a PIC method, we have developed a two-dimensional parallelized PIC code utilizing GPUs. In this presentation, the coupled simulation is presented using FDTD electromagnetic wave solver and PIC method.

*This work was supported by "Development Program of Nano Process Equipments" of Korea Ministry of Knowledge Economy.

11:45

DT4 8 Electric fields measurements in the collisional RF plasma pre-sheath during microgravity conditions JOB BECKERS, DIRK TRIENEKENS, GERRIT KROESEN, *Eindhoven University of Technology* ELEMENTARY PROCESSES IN GAS DISCHARGES TEAM When a plasma comes into contact with a solid body, a space charge region is formed near that surface. This is due to the difference in mobility between the ions and the much lighter electrons. Electric fields in the plasma sheath have demonstrated to be key in almost every plasma application where the acceleration of ions at the border of the discharge is utilized. However, measuring these fields is extremely difficult. In the lower regions of the plasma sheath, where the electric fields are high, they have been measured by Stark Broadening and Stark shift. To gain higher spatial resolution we have recently developed a novel tool using microparticles under hyper-gravity conditions in a centrifuge. Consequently, measuring at positions closer to the plasma bulk than the equilibrium position of the microparticle under normal gravity conditions was impossible. In this paper we present a continuation of this research line towards positions closer to the plasma bulk. This is achieved a combination of measurements of the microparticle equilibrium position under microgravity conditions during parabolic flights and a collisional plasma sheath model. We have been able to measure the electric field throughout the plasma sheath and a part of the pre-sheath region.

SESSION ET1: NANOTECHNOLOGIES I
Tuesday Afternoon, 23 October 2012; Room: Amphitheatre 204 at 13:30; Makoto Kambara, University of Tokyo, presiding

Invited Papers

13:30
ET1 1 Three-Dimensional Integrated Micro Solution Plasmas for Nano Materials Processing
TATSURU SHIRAFUJI, *Osaka City University*

In contrast to the conventional solution chemistry, the solution plasma processing (SPP), which has been invented by Osamu Takai and Nagahiro Saito (Nagoya University), involves accelerated electrons which contribute to generate active chemical species, such as radicals, ions, UV photons and metastable excited atoms. Such active species are expected to enhance through-put of the solution chemistry and to promote the reactions which do not proceed without catalysts. In our previous work, we have successfully obtained glow discharges in water, and applied this technique to modify the surface of nano-materials. Since the previous solution plasma is ignited in a small volume between two stylus electrodes, actual treatment area or volume should be enlarged for practical industrial application. In the case of gas phase processes, large area processing is realized by producing large area plasmas. In the case of SPP, however, large volume plasma in liquid is meaningless, because the most important region is gas-liquid interface. Thus, preparation of large number of tiny plasmas (microplasmas) is rather important in the case of SPP. This can be named as "integrated micro solution plasma." In order to realize the integrated micro-solution plasmas, we have recently utilized interfaces between a plane dielectric plate and porous dielectric material, and successfully obtained large area integrated micro solution plasmas in two dimensions. In this work, we report that three-dimensionally integrated plasmas can be obtained in a porous dielectric material, and demonstrate that Au nano-particles can be synthesized by using this technique. This work has been partly supported by the CREST/JST, the Knowledge Cluster Initiative Tokai Region Nanotechnology Manufacturing Cluster, Grant-in-Aid for Scientific Research on Innovative Areas "Frontier science of interactions between plasmas and nano-interfaces" by the MEXT, and Grant-in-Aid for Scientific Research (C) by the JSPS.

Contributed Papers

14:00

ET1 2 Microplasma-liquid interactions for nanomaterials synthesis JENISH PATEL, PAUL MAGUIRE, DAVIDE MARIOTTI, *Nanotechnology and Integrated BioEngineering Centre (NIBEC), University of Ulster, Northern Ireland, BT37 0QB, UK* Interactions of microplasmas with solid, liquid and/or gas precursors provide new pathways for the synthesis and surface-engineering of nanomaterials. This study is focused on the plasma-induced non-euqilibrium liquid-chemistry (PiLC) as an effective approach to synthesize colloidal metal nanoparticles without using any reducing/capping agents. Highly dispersed gold and silver nanoparticles (NPs) were synthesized in aqueous solutions without any capping agents which explore the opportunities to functionalize the surface of these surfactant-free metal NPs for a better device applications. In particular, various sizes (5 nm to 100 nm) and shapes (e.g. spherical, hexagonal, pentagonal, triangular, etc.) of the gold nanoparticles (AuNPs) were formed with different concentrations of gold precursor. Moreover, conductivity, pH and temperature of the solutions were measured before and after the plasma processing, in order to realize the basic chemistry initiated by plasma in/at liquid surface. Especially, to understand the basic reduction process of AuNPs synthesis by plasma, we measured the presence the of hydrogen peroxide (H_2O_2) which is believed to be a strong reductant for gold and for the first time we demonstrated experimentally that H_2O_2 is the key factor that reduces the gold precursor to AuNPs. These investigations create the opportunities to understand how these microplasmas can be effectively explored to other materials synthesis/processing.

14:15

ET1 3 Diamondoid synthesis by nanosecond pulsed microplasmas generated in He at atmospheric pressure* SVEN STAUSS, TOMOKI SHIZUNO, FUMITO OSHIMA, DAVID Z. PAI, KAZUO TERASHIMA, *Department of Advanced Materials Science, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561, Japan* Diamondoids are sp^3 hybridized carbon nanomaterials that possess interesting properties making them attractive for biotechnology, medicine, and opto- and nanoelectronics. So far, larger diamondoids have been synthesized using the smallest diamondoid (adamantane) as a precursor. For this electric discharges and pulsed laser plasmas generated in supercritical fluids, and hot filament chemical vapor deposition have been used, but these methods are difficult to realize or very time-consuming. We have developed a more convenient approach where diamondoids are synthesized by high-voltage nanosecond pulsed microplasmas (voltage 15 kV_{p-p}, frequency 1 Hz, pulse width 10 ns) generated in He at atmospheric pressure using point-to-plane tungsten electrodes. Adamantane was used as a precursor, and synthesis was conducted for 10^5 pulses at gas temperatures of 297, 373 and 473 K. Energy dispersive X-ray and micro-Raman spectroscopy were conducted to determine the composition of the products, and gas chromatography - mass spectra indicated the formation of diamantane. It was found that synthesis is more efficient at room temperature than at higher temperatures, and time-resolved optical emission spectroscopy suggest that the chemical reactions take place in the afterglow.

*Grant No. 21110002 from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

14:30

ET1 4 Generation of plasmas in supercritical xenon inside microcapillaries for synthesis of diamondoid* FUMITO OSHIMA, CHIKAKO ISHII, SVEN STAUSS, KAZUO TERASHIMA, *The University of Tokyo* Diamondoids are series of sp^3 hybridized carbon nanomaterials that could be applied in various fields such as pharmacy and optoelectronics. In our previous studies, higher order diamondoids were synthesized in supercritical fluid (SCF) plasmas in a batch-type reactor using adamantane ($C_{10}H_{16}$), the smallest diamondoid, as a precursor and seed. However the yield was low and the selectivity was difficult to control. We have developed a continuous flow SCF microplasma reactor that allows discharge volume and residence time to be adjusted. The electrodes consist of a tungsten wire inserted into a fused silica capillary and a sputtered silver outside of the capillary. We dissolved adamantane in supercritical xenon near critical point, and then generated DBDs inside the capillary using a nominal constant xenon flow rate of 0~2.3 mL min^{-1}. Micro-Raman spectra of the synthesized products show peaks that are characteristic of hydrocarbons possessing sp^3 hybridized bonds while gas-chromatography/mass spectrometry spectra indicate the synthesis of diamantane ($C_{14}H_{20}$) and possibly isomers of diamondoids consisting of up to nine cages, nonamantane.

It is suggested that this type of SCF microplasma reactor might be effective not only for synthesis of diamondoids, but also other nanomaterials.

*This work was supported financially in part by a Grant-in-Aid for Scientific Research on Innovative Areas (Grant No. 21110002) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

SESSION ET2: ATMOSPHERIC PRESSURE NANOSECOND PULSED DISCHARGES

Tuesday Afternoon, 23 October 2012
Room: Classroom 203 at 13:30
Anne Bourdon, Ecole Centrale Paris - CNRS, presiding

Contributed Papers

13:30

ET2 1 Numerical Simulation of a Nanosecond-Pulse Discharge for High-Speed Flow Control JONATHAN POGGIE, *Air Force Research Laboratory* IGOR ADAMOVICH, *The Ohio State University* Numerical calculations were carried out to examine the physics of the operation of a nanosecond-pulse, single dielectric barrier discharge in a configuration with planar symmetry. This simplified configuration was chosen as a vehicle to develop a physics based nanosecond discharge model, including realistic air plasma chemistry and compressible bulk gas flow. First, a reduced plasma kinetic model was developed by carrying out a sensitivity analysis of zero-dimensional plasma computations with an extended chemical kinetic model. Transient, one- dimensional discharge computations were then carried out using the reduced kinetic model, incorporating a drift-diffusion formulation for each species, a self-consistent computation of the electric potential using the Poisson equation, and a mass-averaged gas dynamic formulation for the bulk gas motion. Discharge parameters (temperature, pressure, and input waveform) were selected to be representative of recent experiments on bow shock control with a nanosecond discharge in a Mach 5 cylinder flow. The computational results qualitatively reproduce many of the features observed in the experiments, including the rapid thermalization of the input electrical energy and the consequent formation of a weak shock wave. At breakdown, input electrical energy is rapidly transformed (over roughly 1 ns) into ionization products, dissociation products, and electronically excited particles, with subsequent thermalization over a relatively longer time-scale (roughly 10 μs).

13:45

ET2 2 Laser Thomson Scattering Diagnostics of Pulsed Filamentary Discharge Plasmas NIMA BOLOUKI, *Kyushu University* KENTARO TOMITA TEAM, YUKIHIKO YAMAGATA TEAM, KIICHIRO UCHINO TEAM Laser Thomson scattering (LTS) has been applied to measure spatiotemporal evolution of electron density and electron temperature in a pulsed filamentary discharge. The light source of LTS is the second harmonics Nd:YAG laser with a energy of 8 mJ. Also a triple grating spectrometer (TGS) having high rejection rate for stray light is used to measure LTS spectra. In our experimental conditions, non-thermal and non-equilibrium micro-plasmas are generated at round atmospheric pressure. Moreover, the electrode set in this experiment is consisted of a needle electrode and a hemispherical electrode with an inter-electrode gap of 0.5 mm. The total electric charge that flows through the discharge channel vary from 20 nC to 850 nC by changing capacitance in electrical circuit. We could show that the total charge variation leads to increase in electron density from $10^{22}m^{-3}$ to 10^{23} m^{-3}. However, the electron temperature remains almost constant at the main discharge. In order to investigate the streamer phase, we changed the gap up to 16mm, and then performed the LTS method to measure the electron density and electron temperature.

14:00

ET2 3 High Speed Switching Micoplasma in High Pressure Gases* DANI WAKIM, DAVID STAACK, *None* Micro-plasma discharges with switching times approaching 1 ns are studied at pressures from 1 to 16 atm. Applications of these devices are robust high speed switching transistors able to withstand electric interference, high temperatures and harsh environments. Measured discharge conditions at 250 psia in Nitrogen are: gas temperature 2900 K, discharge diameter $\sim$7 μm and electron density $\sim$$10^{17}$ cm^{-3}. High speed switching is achieved by taking advantage of rapid dynamics of instabilities at high pressure and high electron density. The capacitance and inductance of the circuit also significantly affect transients. Tradeoffs are observed in switching times. By reducing capacitances from 10 pF to $\sim$1 pF attainment of steady state conditions can be reduced from 1 us to $\sim$ 20 ns. However current rise times increase from 1 ns at high capacitance to 20 ns at low capacitance. A decrease in switching time with increased pressure is also observed. Also investigated are configurations with a third electrode acting as a gate or trigger and various high temperature (>2000K) materials such as platinum rhodium alloys and ceria stabilized zirconia ceramics for device fabrication.

*Funded by DARPA/US Army grant W911NF-12-1-0007.

14:15

ET2 4 Design and characterization of a plasma actuator for controlling dynamic stall* WILLIAM POLLARD, DAVID STAACK, *Texas A&M University* A repetitive pulsed spark discharge inside of a $\sim$1 mm cavity generates a high velocity (100-600 m/s) gas jets potentially capable of controlling dynamic stall on an airfoil at Re $\sim$1e6. High temperature compressible 2D CFD was used to determine the design and geometry of the actuator slot and plasma cavity. Experimental results measuring the time dependent plasma discharge emission and density variations (using gated ICCD and Schlieren) indicate that the plasma can be modeled as constant volume heating over 100 ns. The energy input to the actuator is controlled by the high voltage and capacitance initiating the discharge. During the discharge air in the cavity is rapidly heated. Temperature and pressure increase 5-10x, causing strong gradients and shocks. The flow is directed using an angled slot. In CFD designed geometries shock fronts and high temperature gas velocities are experimentally determined. The force generated by the actuator is also experimentally determined. Experimental results from the actuator show that velocities of 500 m/s can be achieved through 1mm2 orifices with energy inputs of 50 mJ. The CFD model predicts time scales and velocities similar to those observed, and it also indicates cavity cooling as important in optimizing the actuator pulse repetition rate.

*Funded by NASA SBIR grant NNX12CG07P.

Invited Papers

14:30
ET2 5 Aerospace applications of pulsed plasmas
ANDREY STARIKOVSKIY, *Princeton University*

The use of a thermal equilibrium plasma for combustion control dates back more than a hundred years to the advent of internal combustion (IC) engines and spark ignition systems. The same principles are still applied today to achieve high efficiency in various applications. Recently, the potential use of nonequilibrium plasma for ignition and combustion control has garnered increasing interest due to the possibility of plasma-assisted approaches for ignition and flame stabilization. During the past decade, significant progress has been made toward understanding the mechanisms of plasma chemistry interactions, energy redistribution and the nonequilibrium initiation of combustion. In addition, a wide variety of fuels have been examined using various types of discharge plasmas. Plasma application has been shown to provide additional combustion control, which is necessary for ultra-lean flames, high-speed flows, cold low-pressure conditions of high-altitude gas turbine engine (GTE) relight, detonation initiation in pulsed detonation engines (PDE) and distributed ignition control in homogeneous charge-compression ignition (HCCI) engines, among others. The present paper describes the current understanding of the nonequilibrium excitation of combustible mixtures by electrical discharges and plasma-assisted ignition and combustion. Nonequilibrium plasma demonstrates an ability to control ultra-lean, ultra-fast, low-temperature flames and appears to be an extremely promising technology for a wide range of applications, including aviation GTEs, piston engines, ramjets, scramjets and detonation initiation for pulsed detonation engines. To use nonequilibrium plasma for ignition and combustion in real energetic systems, one must understand the mechanisms of plasma-assisted ignition and combustion and be able to numerically simulate the discharge and combustion processes under various conditions.

SESSION ET3: INDUCTIVELY COUPLED PLASMAS
Tuesday Afternoon, 23 October 2012; Room: Classroom 202 at 13:30; Steve Shannon, North Carolina State University, presiding

Invited Papers

13:30
ET3 1 Ferromagnetic Enhanced Inductive Plasma Sources
VALERY GODYAK, *University of Michigan and RF Plasma Consulting*

Inductively Coupled Plasma, ICP sources, or inductive discharges have been known for over a century. They have been used and studied in past decades mostly in two quite different regimes. At nearly atmospheric pressure, ICPs produce near equilibrium plasmas, while at low gas pressure, in the range of fraction and hundreds of mTorr, ICPs produce highly nonequilibrium plasmas. Low pressure ICPs have been used as ion sources for particle accelerators and thrusters for space propulsion. Recently, interest in low pressure ICPs has been revitalized due to their great advantages in plasma processing and lighting technology. The absence of electrodes, and the capability to provide large plasma densities, and high power transfer efficiency have made these discharges attractive for development of new technologies in various fields. The subject of this presentation is a review of ICP sources enhanced with a ferromagnetic core, FMICP, which found applications in plasma fusion, space propulsion, light sources, plasma chemistry and plasma processing of materials. Introduction of a ferromagnetic core to a magnetic rf circuit of ICP makes its operation close to that of an ideal transformer, thus enhancing its efficiency and power factor. The latter considerably simplifies ICP matching to a rf source. Application of a ferromagnetic core allows for considerable reduction of ICP driving frequency (up to 2-3 orders of magnitude) comparing to the standard in industry of 13.56 MHz. Reduction of the driving frequency allows for practical elimination of capacitive coupling and transmission line effects, inherent to ICP operating at 13.56 MHz. Utilization of lower frequencies also results in more efficient and less expensive rf power sources. However, the most valuable feature of FMICP for plasma processing is its ability for local rf power injection, which promises new possibilities in uniform processing over large substrate areas. The electrical and plasma characteristics of FMICPs, their matching to rf power sources, and their comparison with corresponding characteristics of conventional ICPs without a ferromagnetic core will be discussed in this review for various applications.

Contributed Papers

14:00
ET3 2 High Pressure Discharge Negative Ion Source* LYNN OLSON, *Busek Co., Inc.* JOHN BLANDINO, NIKOLAOS GATSONIS, *Worcester Polytechnic Institute* A high pressure discharge negative ion source has been developed with the goals of high duty cycle, high current, and good reliability, with the ultimate aim of providing a source for a facility such as the Spallation Neutron Source. The discharge itself has been characterized running on hydrogen and helium over pressure ranges of 10s to 100s of torr, with the pressure varied both by changing the flow rate and exit orifice diameter. A key part of the characterization was the power required for the E-H transition as a function of the pressure and gas flow. Running on hydrogen, a biased grid set has been used to extract negative current from a negative ion production region downstream from the discharge exit orifice and an electromagnet has been used to separate electrons from the negative ions. Initial

measured efficiency for negative ion current has been in the range of 1-2 mA/kW.

*This work supported by the Department of Energy.

14:15

ET3 3 Three-Dimensional Electromagnetic Plasma Modeling of Inductively Coupled Plasma Source and Antenna SHAHID RAUF, ANKUR AGARWAL, JASON KENNEY, MING-FENG WU, KEN COLLINS, *Applied Materials, Inc.* Inductively coupled plasmas (ICP) are widely used for etching and deposition in the semiconductor industry. As device dimensions shrink with concomitant decreased tolerance for variability, it is critical to improve plasma and process uniformity in all plasma processes. In ICP systems, one of the major sources of non-uniformity is the radio-frequency (RF) antenna used to generate the electromagnetic wave. Discontinuities at current feed and grounding locations as well as electromagnetic field variations along the antenna coils can perturb the azimuthal electric field, resulting in a non-uniform plasma. For plasma modeling of ICP systems, a related problem is how capacitive coupling from the antenna is accounted for. ICP models have generally considered field variation along the antenna and capacitive coupling using simplified circuit models for the antenna structures. Modern ICP antennas are however quite complicated, making circuit approximations of the antenna too crude for system design. A three-dimensional parallel plasma model is described in this paper, where the full set of Maxwell equations are solved in conjunction with plasma transport equations for the plasma and the antenna. Several examples from the use of this model in ICP system design are presented.

14:30

ET3 4 Evidence of weak plasma series resonance heating in the H-mode of neon and neon/argon inductively coupled plasmas* A.E. WENDT, JOHN B. BOFFARD, R.O. JUNG, CHUN C. LIN, L.E. ANESKAVICH, *University of Wisconsin - Madison* The shape of the electron energy distribution function (EEDF) in low-temperature plasmas governs the relative rates of electron-impact processes that determine key discharge properties. Comparison of EEDFs measured with probes and optical emission [1] in argon and neon inductively coupled plasmas (ICP) has revealed a surplus of high-energy electrons in neon-containing plasmas. The abundance of these extra high energy electrons is correlated with the sheath thickness near the rf antenna and can be reduced by either adding a Faraday shield or increasing the plasma density. These trends suggest an association of the surplus high-energy electrons with stochastic heating of electrons in capacitively-coupled electric fields in the sheath adjacent to the antenna. Conventional stochastic heating, however, is found to be insufficient to account for the EEDF observations, and a comparison of modeled and experimental values of the 13.56 MHz time modulation of select neon emission lines strongly suggests plasma series resonance (PSR) heating adjacent to the ICP antenna as the source of the extra high-energy electrons.

*Supported by NSF grants PHY-1068670 and CBET-0714600, and the Wisconsin Alumni Research Foundation.

[1]Plasma Sources Sci. Technol. **20**, 055006 (2011).

14:45

ET3 5 Model of an Ar/O_2 inductive discharge used for plasma spray deposition CLAUDIA LAZZARONI, MEHRDAD NIKRAVECH, *LSPM, CNRS UPR 3407, Université Paris 13* PASCAL CHABERT, *LPP, CNRS, Ecole Polytechnique, UPMC, Paris XI* A global model of a low pressure radio-frequency inductive discharge proposed to deposit thin layers of zinc oxide, the so-called spray-plasma device, is presented. This device consists in the injection of a precursor in the plasma reactor which is fed with an admixture of argon and oxygen and where the pressure is typically several tens of mTorr. This precursor is an aqueous solution of zinc nitrates, chlorates or acetates, which is transformed into an aerosol thanks to an ultrasonic sprayer. The droplets are then injected in the reactor through an aerosol conditioner and the ZnO layer is deposited on the substrate holder. The global model is based on the numerical resolution of the particle balance equations and the power balance equation. The model is run until the steady state is reached and we obtain the plasma parameters that are the species densities and the electron temperature. A parametric study is done varying the gas pressure, the RF power and the O_2 fraction in the reactor. Throughout the range investigated the electron density is found to be several 10^{17} m^{-3} and the electron temperature is between 2 and 3 eV. A great importance parameter for the deposition process is the flux of the reactive species (O, O^+, O_2^+) on the substrate holder and the model allows a fast parameter range exploration.

SESSION ET4: ION DISTRIBUTION FUNCTIONS
Tuesday Afternoon, 23 October 2012
Room: Salon DE at 13:30
Svetlana Radovanov, Varian Semiconductor Equipment Associates Inc, presiding

Contributed Papers

13:30

ET4 1 2D ion velocity distribution function measurements by laser-induced fluorescence above a radio-frequency biased silicon wafer* NATHANIEL MOORE, WALTER GEKELMAN, PATRICK PRIBYL, *UCLA Department of Physics* YITING ZHANG, MARK KUSHNER, *Electrical Engineering and Computer Science, U. Michigan* Ion dynamics have been measured in the sheath above a 30 cm diameter, 2.2 MHz-biased silicon wafer in a plasma processing etch tool using laser-induced fluorescence (LIF). The velocity distribution function of argon ions was measured at thousands of positions above and radially along the edge of the wafer by sending a planar laser sheet from a pulsed, tunable dye laser into the tool. The RF sheath is clearly resolved. The laser sheet entered the machine both parallel and perpendicular to the wafer in order to measure the distribution function for both parallel and perpendicular velocities/energies (0.4 eV $< E_{max} <$ 600 eV). The resulting fluorescence was recorded using a fast CCD camera, which provided spatial (0.4 mm) and temporal (30 ns) resolution. Data was taken at eight different phases of the 2.2 MHz cycle. The distribution functions were found to be spatially non-uniform near the edge of the wafer and the distribution of energies extremely phase-dependent. Several cm above the wafer the distribution is Maxwellian and independent of phase. Results are compared with simulations; for example, the experimental time-averaged ion energy distribution function compares favorably with a computer model carefully constructed to emulate the device.

*Work supported by the NSF and DOE.

13:45

ET4 2 Space and Phase Resolved Modeling of Ion Energy Angular-Distributions from the Bulk Plasma to the Wafer in Dual Frequency Capacitively Coupled Plasmas* YITING ZHANG, *University of Michigan* NATHANIEL MOORE,

PATRICK PRIBYL, WALTER GEKELMAN, *UCLA-Dept. Physics* MARK J. KUSHNER, *University of Michigan* The control of ion energy and angular distributions (IEADs) is of critical importance for anisotropic etching or conformal deposition in microelectronics fabrication. Dual-frequency capacitively coupled plasmas (CCPs) are being investigated with the goal of having flexible control where the high frequency (HF) controls the plasma density, while the ion energy is mainly determined by the low frequency (LF). However, over select ranges of LF and HF, the IEAD has characteristics of both the LF and HF. To understand this coupling, we report on results of a numerical investigation of phase and spatially resolved transport of ions through the sheath. These results were generated using a two-dimensional plasma hydrodynamics model having an ion Monte Carlo simulation. Inductively coupled plasmas sustained in Ar/O_2 with a multi-frequency bias on the substrate were modeled. The IEADs are tracked as a function of height above the substrate and phase within the rf cycle. The computed results are compared to laser-induced fluorescence (LIF) experiments. We found that the ratios of HF/LF voltage and driving frequency are critical parameters in determining the shape of the IEADs, with evidence of the HF component occurring up to 30 MHz. This tunability may provide additional control for the width and maximum energy of the IEADs.

*Work supported by the NSF and Semiconductor Research Corp.

14:00

ET4 3 Ion energy distributions at the electrodes of high pressure capacitive dual-frequency hydrogen discharges EDMUND SCHÜNGEL, SEBASTIAN MOHR, JULIAN SCHULZE, UWE CZARNETZKI, *Ruhr-University Bochum* Capacitively coupled radio frequency (CCRF) discharges are widely used for surface processing applications, such as thin film solar cell manufacturing. In order to optimize the plasma surface interactions, the fluxes and energy distributions of radicals and ions at the substrate need to be controlled. In particular, the ion energy distribution function (IEDF) plays a crucial role. Previous investigations have shown that the mean ion energy can be changed in low pressure argon discharges via the Electrical Asymmetry Effect (EAE). Here, two consecutive harmonics are applied to the powered electrode. The main control parameter is the phase angle between the frequencies, which allows to adjust the symmetry of the discharge, the DC self bias, and the sheath voltages. In this work, the EAE is investigated in a parallel plate CCRF discharge operated in pure hydrogen at pressures of several hundred Pa. The axial component of the IEDF of the dominant ion species, H_3^+, is measured at the grounded electrode using a plasma process monitor. The results focus on the question how the shape of the IEDF, the mean ion energy, and the total ion flux change as a function of the phase angle. Funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (0325210B).

Invited Papers

14:15

ET4 4 High Energy IED measurements with MEMs based Si grid technology inside a 300mm Si wafer
MERRITT FUNK,* *Tokyo Electron*

The measurement of ion energy at the wafer surface for commercial equipment and process development without extensive modification of the reactor geometry has been an industry challenge. High energy, wide frequency range, process gases tolerant, contamination free and accurate ion energy measurements are the base requirements. In this work we will report on the complete system developed to achieve the base requirements. The system includes: a reusable silicon ion energy analyzer (IEA) wafer, signal feed through, RF confinement, and high voltage measurement and control. The IEA wafer design required carful understanding of the relationships between the plasma Debye length, the number of grids, intergrid charge exchange (spacing), capacitive coupling, materials, and dielectric flash over constraints. RF confinement with measurement transparency was addressed so as not to disturb the chamber plasma, wafer sheath and DC self-bias as well as to achieve spectral accuracy The experimental results were collected using a commercial parallel plate etcher powered by a dual frequency (VHF + LF). Modeling and Simulations also confirmed the details captured in the IED.

*In collaboration with Barton Lane, Lee Chen, Megan Dopple, Jianping Zhao, and Radha Sundararajan, Tokyo Electron, Austin Plasma Lab, Austin, Texas; Yohei Yamazawa and Chishio Kosimizu, Tokyo Electron Yamanashi, Technology Development, Hosaka, Japan.

Contributed Papers

14:45

ET4 5 Single and multi-point ion energy distributions in a VHF+RF commercial plasma reactor measured by novel in-wafer ion energy analyzer BARTON LANE, MERRITT FUNK, LEE CHEN, RADHA SUNDARARAJAN, JIANPING ZHAO, *Tokyo Electron America* A novel, all silicon, minimally perturbing, non-contaminating, in-wafer, 2 and 3 layer ion energy analyzer described elsewhere in this conference is used to measure ion energy distributions for a variety of realistic processing conditions in a commercial VHF + 13.56 MHZ RF reactor with no modifications to its basic geometry or RF delivery system. Spectra with energies as high 1 keV are measured with resolution on the order of 1%. We show data and discuss the splitting of the high energy peaks due to finite ion sheath crossing time effects and how this splitting scales with frequency, power and pressure. We discuss the origin of the charge exchange peaks. We use the identification of atomic and molecular oxygen ion peaks to estimate the resolution of the diagnostic. The effect of VHF in narrowing ion energy distributions and yielding moderate ion energies will be highlighted. Spectra using a multi-point, 2 layer variant of the ion energy analyzer design were obtained at 4 radial locations for a variety of conditions in argon and oxygen plasmas. These spectra quantify center to edge variations and reveal unique spectral features due to pre-existing modifications to the test reactor's upper counter electrode surface.

SESSION FT1: BIOLOGICAL AND BIOMEDICAL APPLICATIONS OF PLASMAS I
Tuesday Afternoon, 23 October 2012
Room: Amphitheatre 204 at 15:30
Gerrit Kroesen, Eindhoven University of Technology, presiding

Contributed Papers

15:30
FT1 1 Plasma Filaments in Dielectric Barrier Discharges Penetrating into High Aspect Ratio Cracks for Sterilization* NATALIA YU. BABAEVA, MARK J. KUSHNER, *University of Michigan* The ability of surface-hugging-plasmas, as produced in dielectric barrier discharges (DBDs), to penetrate into crevices, turn corners and navigate geometrical obstructions, is important in plasma-wound healing and sterilization. In this talk, we discuss results from a computational investigation of the plasma filaments produced in an air DBD and impinging on and penetrating into deep, high aspect ratio cracks in the bottom dielectric. The model used in this work, *nonPDPSIM*, is a plasma hydrodynamics model in which continuity, momentum and energy equations are solved for charged and neutral species with solution of Poisson's equation for the electric potential, concurrent with radiation transport. A Monte Carlo simulation is used to obtain ion energy distributions (IEDs) to surfaces. Cracks are 1 mm deep and 3 μm to 250 μm wide (aspect ratios of 333 to 4). We found that when impinging onto the cracked dielectric, the plasma filament conformally spreads over the surface. The conductive plasma transfers the applied potential to the opening of the crack. The width of the crack, w, then determines the penetration of the plasma. If w is large compared to the filament, the penetration is surface hugging. If w is commensurate with the filament, the plasma fills the crack. If the Debye length is about w or larger, there is not significant penetration. For the conditions investigated, penetration occurred for w > 5-6 μm. IEDs onto the surfaces of the trenches produce transient pulses of ions with energies >150 eV.

*Work supported by the DOE Office of Fusion Energy Science.

15:45
FT1 2 Calculation of Ion Energy Distribution Functions at the Inner Surface of a Pet Bottle During Sterilization Processes* DANIEL SZEREMLEY, SIMON STEVES, RALF PETER BRINKMANN, PETER AWAKOWICZ, *Ruhr-University Bochum* MARK J. KUSHNER, *University of Michigan* THOMAS MUSSENBROCK, *Ruhr-University Bochum* Due to a growing demand for bottles made of polyethylene terephthalate (PET) fast and efficient sterilization processes as well as barrier coating to decrease gas permeation are required. Plasma sterilization is an alternative way of sterilizing PET without using toxic ingredients (e.g. hydrogen peroxide or peracetic acid). To allow investigations in the field of plasma sterilization of PET bottles, a microwave plasma reactor has been developed. A coaxial waveguide combined with a gas-inlet, a modified plasmaline, is used for both coupling the microwave power and injecting the gas mixture into the bottle. One key parameter in the context of plasma treatment of bottles is the ion energy distribution function (IEDF) at the inner surface of the bottle. Additional it is possible to apply a DC bias potential to a metal cage which is placed around the bottle. Numerical results for IEDFs performed by means of the Hybrid Plasma Equipment Model (HPEM) are presented. Plasmas with relevant gas mixtures (Ar and ArO_2) at different pressures and input powers are examined. The numerical results are compared with experimentally obtained data and show very good agreement.

*The authors acknowledge funding by the Deutsche Forschungsgemeinschaft within the frame of SFB-TR 87.

16:00
FT1 3 Optimizing Pulse Waveforms in Plasma Jets for Reactive Oxygen Species (ROS) Production* SETH NORBERG, NATALIA YU. BABAEVA, MARK J. KUSHNER, *University of Michigan* Reactive oxygen species (ROS) are desired in numerous applications from the destruction of harmful proteins and bacteria for sterilization in the medical field to taking advantage of the metastable characteristics of $O_2(^1\Delta)$ to transfer energy to other species. Advances in atmospheric pressure plasma jets in recent years show the possibility of using this application as a source of reactive oxygen species. In this paper, we report on results from a computational investigation of atmospheric pressure plasma jets in a dielectric barrier discharge (DBD) configuration. The computer model used in this study, *nonPDPSIM*, solves transport equations for charged and neutral species, Poisson's equation for the electric potential, the electron energy conservation equation for the electron temperature, and Navier-Stokes equations for the neutral gas flow. A Monte Carlo simulation is used to track sheath accelerated secondary electrons emitted from surfaces and the energy of ions incident onto surfaces. Rate coefficients and transport coefficients for the bulk plasma are obtained from local solutions of Boltzmann's equation for the electron energy distribution. Radiation transport is addressed using a Green's function approach. Various waveforms for the voltage source were examined in analogy to spiker-sustainer systems used at lower gas pressures.

*Work supported by DOE Office of Fusion Energy Science.

16:15
FT1 4 Plasma-generated reactive oxygen species for biomedical applications J.S. SOUSA, *LPGP, CNRS-UPS, Orsay, France* M.U. HAMMER, J. WINTER, H. TRESP, M. DUENNBIER, S. ISENI, *plasmatis, INP, Greifswald, Germany* V. MARTIN, V. PUECH, *LPGP, CNRS-UPS, Orsay, France* K.D. WELTMANN, *INP, Greifswald, Germany* S. REUTER, *plasmatis, INP, Greifswald, Germany* To get a better insight into the effects of reactive oxygen species (ROS) on cellular components, fundamental studies are essential to determine the nature and concentration of plasma-generated ROS, and the chemistry induced in biological liquids by those ROS. In this context, we have measured the absolute density of the main ROS created in three different atmospheric pressure plasma sources: two geometrically distinct RF-driven microplasma jets (μ-APPJ [1] and kinpen [2]), and an array of microcathode sustained discharges [3]. Optical diagnostics of the plasma volumes and effluent regions have been performed: UV absorption for O_3 and IR emission for $O_2(a^1\Delta)$ [4]. High concentrations of both ROS have been obtained ($10^4 - 10^{17}$ cm^{-3}). The effect of different parameters, such as gas flows and mixtures and power coupled to the plasmas, has been studied. For plasma biomedicine, the determination of the reactive species present in plasma-treated liquids is of great importance. In this work, we focused on the measurement of the concentration of

H_2O_2 and NO_X radicals, generated in physiological solutions like NaCl and PBS.

[1]N. Knake *et al.*, J. Phys. D: Appl. Phys. **41**, 194006 (2008).
[2]K. D. Weltmann *et al.*, Pure Appl. Chem. **82**, 1223 (2010).
[3]J. S. Sousa *et al.*, Appl. Phys. Lett. **97**, 141502 (2010).
[4]J. S. Sousa *et al.*, Appl. Phys. Lett. **93**, 011502 (2008).

16:30

FT1 5 Atomic nitrogen measurements in a radio-frequency atmospheric-pressure plasma jet ERIK WAGENAARS, TIMO GANS, DEBORAH O'CONNELL, KARI NIEMI, *York Plasma Institute, Department of Physics, University of York, York, YO10 5DQ, UK* Atmospheric-pressure plasma jets (APPJs) driven with radio-frequency voltages have the potential to be used in a range of new healthcare applications. To guarantee the safety and effectiveness of these new devices, a thorough understanding of the physics and chemistry of these plasmas is needed. The exact mechanisms through which APPJs affect biological materials like cells, bacteria and DNA are largely unknown, however, recent studies suggest the importance of reactive oxygen and nitrogen species (RONS). The starting point for the creation of many of the different RONS is the production of atomic oxygen and nitrogen in APPJs by breaking up oxygen and nitrogen gas molecules. In order to fully understand and control the production and effects of different RONS it is therforte important to measure atomic oxygen and nitrogen species in APPJs. This contribution presents the first direct measurements of atomic nitrogen species in APPJs. The measurements were performed with a two-photon absorption laser-induced fluorescence diagnostic, using 206.65 nm laser photons for the excitation of ground-state N atoms and observing fluorescence light around 744 nm. The APPJ was run with a helium gas flow of 1 slm and varying small admixtures of molecular nitrogen of 0–0.7 vol%. A maximum in the measured N concentration was observed for an admixture of 0.25 vol% nitrogen gas.

16:45

FT1 6 Diagnostic of the surface micro-discharge using spectroscopic methods* YANG-FANG LI, GREGOR MORFILL, *Max Planck Institute for Extraterrestrial Physics* PLASMA HEALTHCARE TEAM A handheld and battery-driven CAP device is designed for clinical studies. The accomplished medical phase I study has shown high bactericidal efficacy *in vitro*, *ex vivo* as well as *in vivo*. Although tests have been done concerning the biological safety and toxic gas emissions accordingly to the electrical safety, the chemical production of this device is not well addressed. In particular, the ozone production remains to be a big issue for safety reasons and reactive Nitrogen and Oxygen species (RNOS) are regarded to the key players for the biological and medical effects of CAPs. Given the application time for the clinical trial would be in the range of 30 seconds, we will present the temporal evolution of several RNOS within running time of a few minutes. The measurement is done mainly by the optical emission and absorption spectroscopies. Depending on the characteristic parameters of the applied voltage signal for discharge, the production of the RNOS may evolve in different profiles. Especially for high power operation, the discharge takes around 30 seconds to reach a steady state. Although the discharge power is found to be the most important factor, the characteristic frequency and even the gas temperature in ambient air, which in our case is the working gas, may alter the yields of several species, for example ozone and atomic Oxygen. The result will help for developing CAP devices for different applications and to design the protocol for the clinical test concerning the efficacy and safety.

*This work was supported by the grant M.TT.A.EXT.00002.

17:00

FT1 7 Transfer of Atmospheric Pressure Plasma Streams Across Dielectric Tubes and Channels* ZHONGMIN XIONG, *University of Michigan* ERIC ROBERT, VANESSA SARRON, JEAN-MICHEL POUVESLE, *GREMI/CNRS-Univ. Orleans* MARK J. KUSHNER, *University of Michigan* Transfer of atmospheric pressure plasma streams refers to the production of an ionization wave (IW) in a tube or channel by impingement of a separately produced IW onto its outer surface. In this paper, we report on a joint numerical and experimental investigation of this plasma transfer phenomenon. The two tubes, source and transfer, are perpendicular to each other in ambient air with a 4 mm separation. Both are flushed with Ne. The primary IW is generated in the source tube by ns to μs pulses of $\pm$25kV, while the transfer tube is electrodeless, not electrically connected to the first and is at a floating potential. The simulations are conducted with *nonPDPSIM*, a 2-dimensional plasma hydrodynamics model with radiation transport. In this model, the 3-d tubes in the experiments are represented by 2-d capillary channels. The experimental diagnostics include ns resolution ICCD imaging. Simulations and experiments show that the primary IW propagates across the inter-tube gap and, upon impingement, induces two secondary IWs propagating in the opposite directions in the transfer tube. Depending on the polarity of the primary IW and the rate of rise (dV/dt) of the voltage pulse, the secondary IWs can have polarities either the same or opposite to that of the primary IW.

*Work supported by US Dept. of Energy and APR Region Centre Plasmed.

17:15

FT1 8 Long and Highly Flexible Micro-Plasma Jet Device for Endoscopic Treatments JAE YOUNG KIM, DANIEL CUTSHALL, *Department of Electrical and Computer Engineering, Center for Optical Materials Science and Engineering Technologies, Clemson University* THOMAS HAWKINS, JOHN BALLATO, *School of Material Science and Engineering, Center for Optical Materials Science and Engineering Technologies, Clemson University* SUNG-O KIM, *Department of Electrical and Computer Engineering, Center for Optical Materials Science and Engineering Technologies, Clemson University* A long and highly flexible micro-plasma jet device made of hollow-core optical fiber has been proposed for use in endoscopic treatment. The fiber which is used has an inner diameter of 350 μm and an outer diameter of 700 μm. The plasma jet device was 165 cm in length and merely 2 millimeters wide at the widest point. The system was configured so that thin wire electrodes were isolated inside of the optical fibers, thereby not allowing contact with the environment at the end of the device where the jet is produced. Such an electrode arrangement allows for great safety while also producing a stable plasma column and jet during treatment inside the patient's body. Despite the small inner diameter and the low gas flow rate, the generated plasma jets are shown to be stable and sufficiently effective at treating cells or germs. The exceptional flexibility and length of the micro-plasma device will enable it to reach diverse areas inside the human body. Plasma devices analogous to the one created have enormous potential for the treatment of a myriad of internal human ailments due to the devices' great flexibility and favorable chemical, medical, and physical properties.

SESSION FT2: PLASMA MODELING AND SIMULATIONS I

Tuesday Afternoon, 23 October 2012; Room: Classroom 203 at 15:30; Haruaki Akashi, National Defense Academy Japan, presiding

Invited Papers

15:30

FT2 1 Simulations of Plasma Sources for Semiconductor Device Manufacturing
PETER VENTZEK, *Tokyo Electron America*

First being applied to etching [1] and deposition [2] more than four decades ago, plasma unit processes are now ubiquitous in the semiconductor industry. However, in many cases the use of plasma discharges for semiconductor process development has far outpaced our fundamental understanding of plasma unit processes. Fortunately, state-of-the-art modeling and simulation is now applied both in the capitol equipment and device manufacturing sectors fortified by close relationships with academic institutions and national laboratories globally. The simulation tableau, modeling and simulation for semiconductor device manufacturing community may be broken into the following categories: new concept development, new process development, equipment physics and equipment engineering. This presentation will focus on simulation modalities that highlight how the physics of production equipment result in beneficial processes. Two classes of examples with be provided [3]. The first will illustrate the behavior of microwave plasma source; the second will explore the electron kinetics associated of capacitively coupled plasma sources. The common thread linking these topics is the importance of the frequency dependence of the electron energy distribution function (eedf) to the fidelity of the simulation results. With respect to the microwave driven plasma sources, in addition to comparing predictions of different modeling approaches to experimental data, the relationship between the microwave network and the plasma dynamics in addition will be highlighted. While the criticality of the eedf to all of capacitively coupled systems will be discussed, particular focus is paid to dc augmented capacitively coupled sources where management of how the ballistic electron population reaches the substrate is critical to process results. Fluid, test particle and full particle-in-cell Monte Carlo simulations will be used to illustrate different discharge behavior.

[1] H. Abe *et al.*, Jpn. J. Appl. Phys. **12**, 154 (1973).
[2] L. L. Alt *et al.*, J. Electrochem. Soc. **110**, 465 (1963).
[3] see companion papers by Upadhyay *et al.*, and Kaganovich *et al.*,

Contributed Papers

16:00

FT2 2 Ion Energy Distribution and Ion Flux Uniformity Studies on Biased Substrate of a HDP-CVD Reactor FEDERICO GALLI, RAJESH DORAI, JAMES CARON, *Lam Research Inc.* High-density plasma CVD (HDP-CVD) reactors are used to fill high aspect ratio device structures with high-quality dielectric films. In these tools deposition and etching coexist to efficiently fill the narrow trenches from the bottom up, while avoiding the creation of voids in the dielectric material. Because of the required fine balance between deposition and etching, an enabling factor of this technology is the ability to carefully control ion flux, ion energy, and the overall process uniformity. Ion energy distribution and ion flux uniformity are modeled for a HDP-CVD commercial reactor where the plasma is generated by an inductively coupled source and a capacitively coupled source at the wafer level. In this work only inert gases (Ar, He, and N2) are used, instead of the complete mixture of gases necessary for deposition. Different pressures, power levels and power ratios between ICP and CCP coupling are the parameters changed to investigate their effects on the ion energy distribution and the ion flux uniformity. An ion energy analyzer is used to measure ion energy distribution and ion flow uniformity and the modeling results are compared with experimental results.

16:15

FT2 3 The effect of frequency-dependent electron swarm parameters on fluid modeling of high-frequency CCP discharges ROCHAN UPADHYAY, SHANKAR MAHADEVAN, *Esgee Technologies Inc.* IKUO SAWADA, MIRKO VUKOVIC, PETER VENTZEK, *Tokyo Electron Limited* LAXMINARAYAN RAJA, *The University of Texas at Austin* Fluid models are computationally the most feasible approach for the multidimensional simulation of reactive CCPs. Fluid models require the specification of species reaction-rate and transport coefficients. For electrons, these closure terms are dependent on the assumed/computed EEDF that depend on the excitation frequency. However the excitation frequency dependence of these electron properties for fluid models are rarely discussed. Here we explore the significance of frequency-dependent electron transport and reaction rate coefficients for high-frequency CCP discharges. We use pre-computed electron properties from a zero-dimensional electron Boltzmann solver which are used in the simulation of an argon CCP at 60MHz and pressures of 15 mTorr and 100 mTorr. A high-resolution computational mesh is developed and used to overcome any uncertainty associated with numerical discretization. We report significant differences in the pre-computed electron reaction-rate and transport coefficients for a 60 MHz EEDF compared to direct-current EEDF or assumed Maxwellian EEDF. The effects of these differences on the discharge structure are found to be significant; clearly emphasizing the importance of using frequency-dependent electron properties in high-frequency CCP models.

16:30

FT2 4 Two-Dimensional (z-θ) Hybrid Fluid-PIC Simulation of Enhanced Cross-field Electron Transport in an Annular $E\times B$ Discharge CHERYL LAM, *Stanford University* EDUARDO FERNANDEZ, *Eckerd College* MARK CAPPELLI, *Stanford*

University We use a numerical model to study quasi-coherent plasma fluctuations and their impact on cross-field electron transport. We consider the case of an annular discharge, subject to a radial magnetic field and an axial electric field. Motivated by experimental evidence of anomalously high electron mobility across the magnetic field in Hall thruster discharges, we choose a two-dimensional axial-azimuthal (z-θ) simulation geometry. The model includes a continuously-replenished heavy (Xe) neutral background, with an imposed radial magnetic field and an applied axial electric potential. We use a hybrid fluid-Particle-In-Cell treatment; the ion and neutral species are treated as collisionless particles, while the electrons are treated as a fluid continuum. Using numerical simulations to resolve the azimuthal electron dynamics, we focus on understanding the role played by fluctuations, particularly those that propagate with components perpendicular to both the applied electric and magnetic fields. Preliminary simulations predict dispersive "tilted" wave fluctuations in the plasma density and electron velocities. These fluctuations appear to contribute to an enhanced overall electron mobility, which is significantly higher than that based on classical scattering.

16:45

FT2 5 A new approach for the determination of electron transport coefficients* MARKUS M. BECKER, DETLEF LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* Hydrodynamic models are commonly used for the theoretical description of gas discharge plasmas at moderate and high pressure. The full set of hydrodynamic equations is frequently simplified by means of the drift-diffusion approximation for electron particle and energy densities. Their diffusion coefficients and mobilities are usually determined from the solution of the zero-dimensional Boltzmann equation using expansion techniques and are finally incorporated into the fluid model as functions of the mean electron energy. The present contribution points out that common approaches are subject to serious restrictions regarding the description of nonlocal phenomena. A new drift-diffusion model for the treatment of the electron transport is suggested which avoids some of the drawbacks of the classical approaches. In particular, it is shown that the new model provides a better approximation of the electron heat flux, which is known to be crucial for an accurate description of the electron component in non-thermal discharge plasmas. To demonstrate its applicability, results for spatially one dimensional argon glow discharge plasmas at low and atmospheric pressure are presented and discussed.

*This work was supported by DFG within the SFB TRR24.

17:00

FT2 6 Comparison of a Global Model to Semi-Kinetic Fluid Simulations for Atmospheric Pressure Radio- Frequency Capacitive Discharges KARI NIEMI, DEBORAH O'CONNELL, TIMO GANS, *York Plasma Institute, Department of Physics, University of York, York YO10 5DD, UK* A global model of a homogeneous plasma bulk oscillating between electron-free rf sheaths is developed. Particle and power balance, including ohmic heating loss for bulk electrons and ions in the sheaths, yields bulk electron temperature and density. Explicit time dependence of the reduced bulk electric field and, correspondingly, of the total ionization rate and electron transport coefficients is accounted for. Results as a function of the rf power density for a gas mixture of 0.5 vol% oxygen in helium at atmospheric pressure within a 1mm discharge gap are presented and compared to a 1D-fluid simulation, which is capable to describe the electron dynamics despite of a limited plasma-chemical reaction scheme. The quality of agreement is critically analysed and correlated to the individual global model assumptions. Possibilities of coupling the global model to comprehensive discharge chemistry models are discussed.

17:15

FT2 7 Analytical Model for the Microwave Driven Double ICP Plasma Jet* ALI ARSHADI, DENIS EREMIN, THOMAS MUSSENBROCK, RALF PETER BRINKMANN, *Theoretical Electrical Engineering, Ruhr University Bochum, D-44780 Bochum, Germany* PETER AWAKOWICZ, *General Electrical Engineering and Plasma Technology, Ruhr-University Bochum, D-44780 Bochum, Germany* HORIA-EUGEN PORTEANU, ROLAND GESCHE, *Ferdinand-Braun-Institut, Berlin, Germany* KLAUS WANDEL, *SENTECH Instruments GmbH, Berlin, Germany* For many technical applications, microwave driven plasma jets are possible alternatives to conventional RF plasma sources. Their construction is uncomplicated and they have the advantages of small size and large electrical efficiency. The microwave driven double ICP plasma jet is a recently developed variant. The core of the device is a cavity resonator with a resonance frequency close to 2 GHz. In good approximation, the resonator can be described as a circuit of two cylindrical one-turn coils parallel to a planar capacitor. Inside the coils are ceramic tubes which contain the plasma. Electromagnetic fields in the bulk and sheath reagion can be computed based on Maxwell's equations and the cold plasma model considering boundary conditions and the electric field due to the source on metalic cavity. A comparison of the simulation results with experimental data is performed.

*Financial support by the Ruhr-University Bochum Research School is gratefully acknowledged.

SESSION FT3: ELECTRON-IMPACT IONIZATION

Tuesday Afternoon, 23 October 2012; Room: Classroom 202 at 15:30; Allison Harris, Henderson State University, presiding

Invited Papers

15:30

FT3 1 Single and double ionization of helium: a Sturmian approach*

LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France*

The quantal description of three-body break-up processes is a notoriously difficult problem, one major obstacle being the imposition of proper asymptotic boundary conditions. In this contribution, single and double ionization of helium are investigated through a Sturmian approach in hyperspherical coordinates. A similar approach, in spherical coordinates, has been applied successfully to a number of two-electron systems (see, e.g., [1]). It is known, though, that for the three particles break-up the global asymptotic behavior (Peterkop) is best described in hyperspherical coordinates. The use of these more natural coordinates, within a Sturmian approach, provide the basis functions with more adequate outgoing asymptotic conditions [2]. In this way the scattering wave function expansion is restricted to the region where the interaction between the particles takes place, considerably increasing the convergence rates. The application of the recently proposed hyperspherical Sturmian approach [2] is applied to ionization processes of helium. The scattering wave function and related differential cross sections will be presented.

*This work has been developed within the activities planned in the French-Argentinian programme ECOS-Sud A10E01, and in collaboration with G. Gasaneo (Universidad Nacional del Sur, Argentina) and D.M. Mitnik (Universidad de Buenos Aires, Argentina).

[1]A. L. Frapiccini *et al.*, J. Phys. B **43**, 101001 (2010); J. M. Randazzo *et al.*, Phys. Rev. A **84**, (2011).
[2]G. Gasaneo and L. U. Ancarani, J. Phys. A **45**, 045304 (2012).

Contributed Papers

16:00
FT3 2 Nonperturbative B-Spline R-Matrix with Pseudostates Calculations for Electron Impact Ionization of Helium* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* The theoretical and numerical approach used in a recent publication [1] describing a nonperturbative treatment of ionization and simultaneous ionization plus excitation of helium by electron impact will be discussed. We then present a variety of comparisons between the present predictions, experimental data, and results from other nonperturbative theories, such as convergent close-coupling and time-dependent close-coupling, for ionization without excitation. The overall excellent agreement with the other available data provides confidence in using the B-spline R-matrix with pseudostates approach for this benchmark system, as well as extending it to more complex situations for which no other nonperturbative methods are currently available.

*Work supported by the United States National Science Foundation under PHY-0903818 and PHY-1068140, and by the TeraGrid/XSEDE allocation TG-PHY090031.

[1]O. Zatsarinny and K. Bartschat, Phys. Rev. Lett. **107**, 023203 (2011).

16:15
FT3 3 Low energy (e,2e) experimental and theoretical 3-dimensional study of Neon* SADEK AMAMI, DON MADISON, *Missouri University S&T* HARI SAHA, *University of South Florida* THOMAS PFLUEGER, XUEGUANG REN, ARNE SENFTLEBEN, ALEXANDER DORN, JOACHIN ULLRICH, *Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany* Three-dimensional triple differential cross sections have been calculated and measured for 61eV electron-impact ionization of the 2p state of neon. Three-dimensional distributions for the ejected electron will be presented for a fixed incident projectile energy and scattered projectile angles ranging between 20 degrees and 70 degrees and ejected electron energies ranging between 2eV to 20eV. The theoretical model used for the calculations is the DWBA (distorted wave Born approximation). The importance of PCI (post collision interaction between the scattered and ejected electron) will be examined by either including or excluding this effect in the final state wavefunction. The importance of the interaction between the ejected electron and the residual atomic electrons will be examined by comparing results using distorted waves calculated in a static potential with Hartree-Fock distorted waves.

*Work supported by NSF under grant number PHY-1068237.

Invited Papers

16:30
FT3 4 Relativistic Calculations of Electron Ionization of Xenon
ALLAN STAUFFER, *York University, Toronto ON Canada*

We are interested in the ionization of heavy atoms by electrons of intermediate energy. Since the incident particles do not have relativistic energies, the question arises as to why a relativistic treatment of this process is preferable. The answer lies both in the treatment of the target as well as the incident particle. In our case, a relativistic treatment of the target system is done within the j-j coupling scheme where the spin and angular momenta of each electron are coupled to a total angular momentum j. Thus the valence p shell of xenon is split into two subshells, one with j = 3/2 and one with j = 1/2. Calculations of the target wave functions can be readily carried out using an available program [1]. There is a fine structure splitting of 1.31 eV between these two subshells. Thus the energy required to ionize these two subshells is sufficiently different that they can be distinguished experimentally. The Dirac equations which describe the free electrons in a distorted-wave approximation with non-local exchange explicitly contain the spin of the electron. Thus the treatment of spin-polarized scattering is straightforward and does not require any recoupling of angular momenta as in a non-relativistic scheme. Recent experiments [2,3] have measured the ionization of the j = 3/2 valence electrons of xenon when the incident electron makes an arbitrary angle with the plane containing the outgoing electron which have identical energies. We will present calculations for this process to compare with the measurements and discuss the results in terms of the models proposed for the scattering mechanisms giving rise to these non-coplanar events.

[1]P. Jonsson, X. He, C. Froese Fischer, and I. P. Grant, Comput. Phys. Commun. **177**, 597-622 (2007).
[2]K. L. Nixon, A. J. Murray, and C. Kaiser, J. Phys. B **43**, 085202 (2010).
[3]K. L. Nixon and A. J. Murray, Phys. Rev. A **85**, 022716 (2012).

Contributed Papers

17:00

FT3 5 Importance of Molecular alignment in (e,2e) collisions* ESAM ALI, DON MADISON, *Missouri University of Science and Technology* ALLISON HARRIS, *Henderson State University* JULIAN LOWER, *Max-Planck-Institut fur Kernphysik* ERICH WEIGOLD, *Australian National University* CHUANGANG NING, *Tsinghua University* Most experiments measuring electron-impact ionization of molecules do not determine the orientation of the molecule at the time of ionization. One way to determine the orientation is to simultaneously ionize the molecule and excite the residual ion to a state that will dissociate. The orientation of the molecule can then be determined by detecting one of the dissociation fragments since the fragments will leave in the direction of orientation. Experimental and theoretical TDCS (triple differential cross sections) results will be presented for excitation-ionization of three excited states of H2 for three different orientations of the molecule at incident electron energy of 176 eV.

*Work Supported by NSF under grant number PHY-1068237.

17:15

FT3 6 Single differential cross sections for electron-hydrogen ionization: the quantum mechanical flux formula revisited JUAN MARTIN RANDAZZO, *Centro Atomico Bariloche, Argentina* LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* GUSTAVO GASANEO, *Universidad Nacional del Sur, Bahia Blanca, Argentina* FLAVIO COLAVECCHIA, *Centro Atomico Bariloche, Argentina* One way of extracting single differential cross sections (SDCS) for the electron-hydrogen ionization process is based on using the quantum mechanical flux operator evaluated at asymptotic distances. This procedure is formally correct; however, numerical evaluations are necessarily performed at finite distances. As a consequence, unphysical oscillations appear at very unequal energy sharing [1] and, for this reason, the flux formula was somehow discarded by the community. In this contribution we propose two corrections based on alternative ways of defining the energy fraction. The first one uses the components of the probability flux instead of the usual asymptotic kinematical (or geometrical) approximation. The second comes from a finite distance energy reinterpretation related to a simple, classical, energy conservation analysis. Results of calculations for the s-wave approximation of the e-H processes, performed at various impact energies and for both singlet and triplet symmetry, are presented. Once our flux formula corrections are applied, the unphysical behavior previously observed is removed, and our SDCS results compare favorably with benchmark theoretical data.

[1]M. Baertschy *et al.*, Phys. Rev. A **60**, R13 (1999).

SESSION FT4: ADVANCED LASER BEAM DIAGNOSTICS

Tuesday Afternoon, 23 October 2012; Room: Salon DE at 15:30; Timo Gans, University of York, presiding

Invited Papers

15:30

FT4 1 Laser scattering for temporal and spatial diagnostic of low temperature plasmas
JOSE MARIA PALOMARES LINARES,* *Eindhoven University of Technology*

Many recent industrial and technological applications like surface etching, inorganic films deposition, polymerization of surfaces or sterilization are developed within the field of low temperature plasmas. To study, monitor and model plasma processes is of great importance to have diagnostic tools that can provide reliable information on different plasma parameters. In general, laser scattering techniques provide a direct and accurate method for plasma diagnostic with spatial and temporal resolution. Laser Thomson scattering is used for the diagnostic of electron density and temperature, two of the most important parameters in low temperature discharges. With a similar setup Rayleigh and Raman scattering techniques are used for the diagnostic of gas density and temperature. In this contribution we deal with the different technical and theoretical aspects that are required for the application of these laser scattering techniques. Of special importance are the detection limit, laser stray light rejection and laser perturbations of the plasma. The present study is performed on different low temperature microwave discharges, both at low and atmospheric pressure. The laser scattering techniques provide information on the spatial distribution of the mentioned plasma parameters over different discharge conditions, including small micro-plasmas. Similarly, the temporal evolution of pulsed plasmas is studied, unraveling the features of the switching on and off phases of the discharges.

*In collaboration with S. Hubner, E.A.D. Carbone and J.J.A.M. van der Mullen.

Contributed Papers

16:00

FT4 2 Transient characteristics of a pulsed helium positive column as measured with laser-collision induced fluorescence* ED BARNAT, *Sandia National Laboratories* VLADIMIR KOLOBOV, *CFDRC* The two dimensional laser-collision induced fluorescence (2D LCIF) diagnostic technique is extended to modest pressures (0.1 Torr to 10 Torr) and is then utilized to examine the evolution of helium positive column in response to a pulsed current (up to 1.5 A). Temporally and spatially resolved measurements of the species in the pulsed column such as excited state distributions, electron densities and "effective electron temperatures" are obtained using the LCIF technique. It is observed, that during the initial response of the column to the applied pulse, the radial dependence of excited state species (23P state of helium) tracks that of the electron densities. On the other hand, significant deviation between radial profiles of the excited species and the radial profile of the electron densities is observed as the column evolves in time. While the electron densities remain radially peaked on the axis of the discharge, the excited state distribution flattens out at lower pressures (<2 Torr) and becomes peaked off axis at the higher pressure bound studied (>3 Torr). Global measurements of discharge current and line-integrated densities obtained with microwave interferometry are used both to calibrate the laser measurements as well as to ascertain reduced electric fields (E/N) and electron temperature. Trends observed in spatially resolved measurements are discussed and compared to simulation results.

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

16:15

FT4 3 Development of a Time Synchronized CW-Laser Induced Fluorescence Measurement for Quasi-Periodic Oscillatory Plasma Discharges* NATALIA MACDONALD, MARK CAPPELLI, *Stanford University* WILLIAM HARGUS, JR, *Air Force Research Laboratory, Edwards AFB* An advanced CW laser induced fluorescence diagnostic technique, capable of correlating high frequency current fluctuations to the resulting fluorescence excitation lineshapes, has been developed. This presentation describes this so-called "Sample-Hold" method of time-synchronization, and provides the steps taken to validate this technique, including simulations and experimental measurements on a 60 Hz Xe lamp discharge. Initial results for time-synchronized velocity measurements on the quasi-periodic oscillatory mode of a magnetic cusped plasma accelerator are also presented. These results show that the positions of the ionization and peak acceleration regions in the device vary over the course of a discharge current oscillation.

*Research is funded through the Air Force Office of Scientific Research with Dr. M. Birkan as grant monitor.

Invited Papers

16:30

FT4 4 Non-linear optical diagnostic studies of high pressure non-equilibrium plasmas*
WALTER LEMPERT, *Ohio State University*

Picosecond Coherent Anti-Stokes Raman Spectroscopy (CARS) is used for study of vibrational energy loading and relaxation kinetics in high pressure nitrogen and air nsec pulsed non-equilibrium plasmas in a pin-to-pin geometry. It is found that ~33% of total discharge energy in a single pulse in air at 100 torr couples directly to nitrogen vibration by electron impact, in good agreement with master equation modeling predictions. However in the afterglow the total quanta in vibrational levels 0–9 is found to increase by a factor of approximately 2 and 4 in nitrogen and air, respectively, a result in direct contrast to modeling results which predict the total number of quanta to be essentially constant. More detailed comparison between experiment and model show that the VDF predicted by the model during, and directly after, the discharge pulse is in good agreement with that determined experimentally, however for time delays exceeding ~10 μsec the experimental and predicted VDFs diverge rapidly, particularly for levels $v = 2$ and greater. Specifically modeling predicts a rapid drop in population of high levels due to net downward V-V energy transfer whereas the experiment shows an increase in population in levels 2 and 3 and approximately constant population for higher levels. It is concluded that a collisional process is feeding high vibrational levels at a rate which is comparable to the rate at which population of the high levels is lost due to net downward V-V. A likely candidate for the source of additional vibrational quanta is the quenching of metastable electronic states of nitrogen to highly excited vibrational levels of the ground electronic state. Recent progress in the development and application of psec coherent Raman electric field and spontaneous Thomson scattering diagnostics for study of high pressure nsec pulsed plasmas will also be presented.

*This work supported by the DOE and NSF.

Contributed Papers

17:00

FT4 5 Cavity ringdown measurements of OH radicals in microwave induced argon plasma assisted combustion of methane/air mixtures* WEI WU, CHUJI WANG, *Mississippi State University* LASER SPECTROSCOPY AND PLASMA TEAM In order to study the mechanism of plasma assisted combustion, we have developed a system that injects a nonthermal low temperature atmospheric argon plasma into the burning flame of lean methane/air mixtures. The experimental results demonstrated the flammability enhancement of plasma assisted combustion in the lean flame of a fuel equivalence ratio as low as 0.2. In the argon plasma assisted combustion flame, we observed three different zones which were pure argon plasma zone, plasma-flame interacting zone, and pure flame zone. Optical emission studies showed distinct spectroscopic fingerprints of each zone. The emission intensities of OH radicals increased dramatically moving from pure plasma zone to plasma-flame interacting zone, and dropped severely from plasma-flame interacting zone to pure flame zone. In addition to the optical emission spectroscopy study, cavity ringdown spectroscopy (CRDS) was also applied in the measurements of absolute ground state OH radical number densities in the plasma assisted combustion flame. Results showed that the ground state OH radical number densities in the pure flame zone are on the order of 10^{15} molecule/cm^3, and increasing within the range of first few millimeters from the combustor nozzle.

*This work is supported by the National Science Foundation through the grant No. CBET-1066486.

17:15

FT4 6 Development of novel atomic absorption spectroscopic method using optical frequency comb KEIICHIRO URABE, *The University of Tokyo* OSAMU SAKAI, *Kyoto University* For progress of atomic absorption spectroscopy including plasma diagnostics, we proposed a novel system of laser spectroscopic method for single electronic transitions using a frequency-comb laser source. The optical frequency comb is one of the newly developed coherent light sources and has potentials to be applied not only to accurate measurement of laser frequencies but also to various infrared spectroscopic measurements. In the novel method, the frequency-comb laser beam passes through tested plasma and then the frequency-comb laser beam is merged with an additional single-wavelength laser beam to generate beat signals by the interference. A power spectrum of the beat signals in the merged laser beam is recorded with a bandwidth of several tens of GHz which is sufficient to analyze whole spectrum of a single electronic transition. This method, named a frequency-comb interference spectroscopy (FCIS), enables us to measure single-transition absorption spectra without using a large-scale spectrometer or scanning the laser-beam frequency. We have evaluated the FCIS method in absorption profile measurements of argon metastable atoms in a small RF discharge.

SESSION GT1: A SCIENTIFIC TRIBUTE TO PROFESSOR LEV D. TSENDIN

Tuesday Evening, 23 October 2012
Room: Classroom 202 at 18:00
Allison Harris, Henderson State University, presiding

Contributed Papers

18:00

GT1 1 Introduction: Lev Tsendin's Contributions into LTP
IGOR KAGANOVICH, *Princeton Plasmas Physics Laboratory*

18:05

GT1 2 Lev Tsendin as Mentor

18:15

GT1 3 Lev Tsendin as Scientist: Part I

18:30

GT1 4 Lev Tsendin as Scientist: Part II

18:45

GT1 5 DISCUSSION

SESSION GT2: WORKSHOP ON PLASMA DATA EXCHANGE PROJECT

Tuesday Evening, 23 October 2012; Room: Classroom 203 at 19:00; Annarita Laricchiuta, CNR IMIP Bari, presiding

Invited Papers

19:00

GT2 1 Introduction

19:10

GT2 2 State-of-the-Art Experimental Techniques and Results for Low Energy Electron Collisions with Simple Molecules*

STEPHEN BUCKMAN, *Centre for Antimatter-Matter Studies, The Australian National University*

Electron collisions with simple molecular systems (diatomics and small polyatomics) play an important role in most discharge-based devices and environments. Even in cases where large precursor molecules are involved, say for example in a plasma processing environment, dissociation and dissociative attachment lead to the production of smaller molecules, perhaps radicals, whose interactions can then play an important part in the dynamics of the discharge. This paper will attempt to describe the current state of the art for measurements of processes such as elastic scattering, rotational, vibrational and electronic excitation, dissociative attachment, and ionization of small molecular species by electron impact. Examples of absolute cross sections that arise from such measurements will be provided and compared, where possible, with contemporary theoretical calculations. The collaboration between experiment and theory is of critical importance in the context of "Plasma Data Exchange," as benchmarked theory will play an significant role in providing data for the many, perhaps majority, of processes that cannot be easily measured.

*Supported by the Australian Research Council.

19:40

GT2 3 LXCat project: web interface update to the database

SERGEY PANCHESHNYI, *ABB Switzerland Ltd., Corporate Research (on leave from LAPLACE, Toulouse, France)*

The LXCat project is a community-wide effort to make available, via an open-access website, data needed for modeling low temperature plasmas. More than 20 groups around the world have and are continuing to contribute data to this project which accounts of more than 100 thousand of records for more than 400 species in 2012. One of the project objectives this past year has been to restructure the databases and to rewrite the interface so as to merge into a single project the LXCat databases for electron data with those from ICEcat for ion data. The new structure allows for easy upgrades or extensions to include other data types or output formats. A particular effort this year was devoted to the new implementation of notes section and discussion board that allows users to have an easier access to evaluation results and comments produced by the advising committee of the project and other users. Finally, the results of calculated swarm parameters can now be directly compared with available experimental results. The new site address is http://www.lxcat.net.

20:00
GT2 4 The Phys4Entry database*

ANNARITA LARICCHIUTA, *CNR IMIP Bari*

The Phys4Entry DB is a database of state-selected dynamical information for elementary processes relevant to the state-to-state kinetic modeling of planetary-atmosphere entry conditions. The DB is intended to the challenging goal of complementing the information in the existing web-access databases, collecting and validating data of collisional dynamics of elementary processes involving ground and excited chemical species, with resolution on the electronic, vibrational and rotational degrees of freedom. Four relevant classes of elementary processes are considered, i.e. electron-molecule collisions, atom/molecule-molecule collisions, atom/molecule surface interaction and photon-induced processes, constructing a taxonomy for process classification. Data populating the DB are largely originated by the coordinated research activity done in the frame of the Phys4Entry FP7 project, considering different theoretical approaches from quantum to semi-classical or quasi-classical molecular dynamics. Nevertheless the results, obtained in the Bari plasma chemistry labs in years of research devoted to the construction of reliable state-to-state kinetic models for hydrogen and air plasmas, are also transferred to the DB. Two DB interfaces have been created for different *roles* allowed to different *actions*: the CONTRIBUTOR, uploading new processes, and the INQUIRER, submitting queries, to access the complete information about the records, through a graphical tool, displaying energy or roto-vibrational dependence of dynamical data, or through the *export* action to download ascii datafiles. The DB is expected to have a significant impact on the modeling community working also in scientific fields different from the aerothermodynamics (i.e. fusion, environment, ...), making practicable the state-to-state approach.

*European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 242311.

Contributed Papers

20:30
GT2 5 Roundtable

SESSION HW1: PLASMA SHEATHS II

Wednesday Morning, 24 October 2012; Room: Amphitheatre 204 at 8:00; Ralf Peter Brinkmann, Ruhr-Universität Bochum, presiding

Invited Papers

8:00

HW1 1 Plasma-Sheath Model

KARL-ULRICH RIEMANN, *Ruhr-Universität Bochum*

In typical gas discharges a quasineutral plasma is shielded from a negativ absorbing wall by a thin positive sheath that is nearly planar and collision-free. The subdivision of "plasma" and "sheath" was introduced by Langmuir and is based on a small ratio of the electron Debye lenghth λ_D to the dominant competing characteristic plasma length ℓ. Depending on the special conditions, ℓ may represent, e.g., the plasma extension, the ionization length, the ion mean free path, the ion gyro radius, or a geometric length. Strictly speaking, this subdivion is possible only in the asymptotic limit $\lambda_D/\ell \to 0$. The asymptotic analysis results in singularities at the "sheath edge" closely related to the "Bohm criterion." Due to these singularities a direct smooth matching of the separate plasma and sheath soltions is not possible. To obtain a consistent smooth transition, the singular sheath edge must be bridged by an additinal narrow "intermediate" model zone accounting both for plasma processes (e.g., collisions) and for the first build up of space charge. Due to this complexity and to different interpretations of the "classical" papers by Langmuir and Bohm, the asymptotic plasma-sheath concept and the definition of the sheath edge were questioned and resulted in controversies during the last two decades. We discuss attempts to re-define the sheath edge, to account for finite values of λ_D/ℓ in the Bohm criterion, and demonstrate the consistent matching of plasma and sheath. The investigations of the plasma-sheath transition discussed so far are based on a simplified fluid analysis that cannot account for the essential inhomogeneity of the boundary layer and for the dominant role of slow ions in space charge formation. Therefore we give special emphasis to the kinetic theory of the plasma-sheath transition. Unfortunately this approach results in an additional mathematical difficulty caused by ions with zero velocity. We discuss attempts to avoid this singularity by a modification of the kinetic Bohm criterion and investigate the influence of slow ions on the structure of the plasma-sheath transition. The most important conclusions are illustrated with selected examples.

Contributed Papers

8:30

HW1 2 Accuracy of the step sheath approximation MARK SOBOLEWSKI, *National Institute of Standards and Technology* In modeling plasma sheaths, it is useful to approximate the electron density profile by a sharp, step-like drop between a quasineutral region and an electron-free region. This approximation allows rapid and efficient numerical calculations of sheath properties and, when combined with other assumptions, allows predictions for sheath properties to be calculated analytically. Nevertheless, the approximation must result in some loss of accuracy. Here, the accuracy of the step approximation was investigated by comparisons with exact solutions for Poisson's equation in the sheath and with experimental measurements of current and voltage waveforms and ion energy distributions. In general, the errors introduced by the step approximation are small but not negligible. The resulting errors in current and voltage are noticeable during the part of the rf cycle when the sheath is nearly collapsed. The effects on the ion energy distribution are most noticeable in the amplitude of the low-energy peak, which is sensitive to the choice of boundary conditions on the plasma side of the step. Using the exact Poisson solution in place of the step approximation results in a modest improvement in the agreement with experiment.

8:45

HW1 3 STUDENT AWARD FINALIST: A Kinetic Theory of Planar Plasma Sheaths Surrounding Electron Emitting Surfaces* J.P. SHEEHAN, *University of Wisconsin - Madison* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory* NOAH HERSHKOWITZ, *University of Wisconsin - Madison* YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* It has long been known that electron emission from a surface significantly affects the sheath at that surface. Typical fluid theory of a planar sheath with emitted electrons assumes that the plasma electrons follow the Boltzmann relation and the emitted electrons are emitted with zero energy and predicts a potential drop of $1.03T_e$ across the sheath at a floating boundary. By removing the assumption that all plasma electrons entering the sheath are reflected back into the bulk plasma (i.e. the Boltzmann relation) and considering electrons lost to the wall, we find that the predicted sheath potential is reduced to $0.91T_e$. Using a kinetic description of the emitted electrons, assuming a half Maxwellian distribution with temperature T_{ee}, greatly affects the sheath potential. We show that kinetic theory predicts that the sheath potential significantly depends on the plasma to emitted electron temperature ratio. For example, we predict that an emissive probe ($T_{ee} = 0.2$ eV) in a plasma with $T_e = 1$eV will have a sheath potential of $0.51T_e$. Additionally, it is noted that the electron velocity distribution function in the sheath is unstable to the two-stream instability.

*This work was supported by US Department of Energy grants No. DE-AC02-09CH11466, and No. DE-FG02-97ER54437, the DOE Office of Fusion Energy Science Contract DE-SC0001939, and the Fusion Energy Sciences Fellowship Program.

9:00

HW1 4 Characteristics of Sheath and Presheath Recovery during Pulse Fall Time JAE-MYUNG CHOE, KYOUNG-JAE CHUNG, Y.S. HWANG, GON-HO KIM, *Department of Energy Systems Engineering, Seoul National University* Recovery motion of sheath and presheath is investigated with various fall times of negative bias on the target. Experimental observation was carried out with the collisionless argon plasma and the various pulses with fast and slow fall times which are shorter and longer than the ion transition time scaled of $3/\omega_{pi}$ (ω_{pi}=ion plasma frequency), respectively. Electrical probe was employed to measure the density distribution. Ion distribution and speed near the target are important factors in determining the position of sheath. For the slow fall time, sheath and presheath boundaries recover with the same speed. Child-Langmuir sheath continuously persists due to enough time to rearrange ions and electrons. For the fast fall time, ion matrix sheath, which is immediately responding to the target voltage, leads the recovery of sheath with supersonic speed. Presheath follows ion inertia that was formed at the plateau time and its speed does not follow the speed of the sheath. Voltage-responding electrons enhance the ion diffusion from the bulk plasma, resulting in the plasma filling in the depletion region. For the intermediate fall time ($badhbox3/\omega_{pi}$), the transformation from ion matrix to Child-Langmuir sheath occurs after ion responds. Detailed results will be presented.

9:15

HW1 5 Numerical simulation of pulsed plasma sheath dynamics in an oblique magnetic field ABOLFAZL MAHMOODPOOR, HAMID GHOMI, SHAHRYAR MIRPOUR, *DBD Laboratory, Laser and Plasma Research Institute of Shahid Beheshti University, Evin, Tehran, Iran* DBD COLLABORATION During past several years many authors [1-2] have investigated plasma sheath structure in an oblique magnetic field, that called magnetized plasma sheath, and their work is mainly in steady state case. In this paper, the dynamic of magnetized pulsed plasma sheath are simulated. We applied an exponentially voltage to the cathode and investigate the temporal and spatial evolution of electric field, ion and electron density. For implement of our main motivation, we used two dimensional fluid model and solved numerically Poisson's equation, continuity and momentum transfer equations for ions by FDT method to determine electric potential, density and speed of ions. To complete our equations system, also assume that electron density identified by Boltzman equation. Therefore we consider a plasma sheath with two dimensions coordinate space and three dimensions of speed. It is shown that electric field of pre-sheath, ion and electron density fluctuate during pulse time and spatial length of electron density fluctuation increase with increasing of magnetic field magnitude.

[1]X. Zou, J.-y. Liu, Y. Gong, Z.-X. Wang, Y. Liu, and X.-G. Wang, *Vacuum* **73**, 681–685 (2004).

[2]M. M. Hatami, A. R. Niknam, and B. Shokri, *Vacuum* **83**, 231–234 (2009).

SESSION HW2: PLASMA ETCHING I

Wednesday Morning, 24 October 2012; Room: Classroom 203 at 8:00; Makoto Sekine, Nagoya University Japan, presiding

Invited Papers

8:00

HW2 1 Time-Multiplexed Deep Silicon Etching

LAWRENCE OVERZET,* *The University of Texas at Dallas*

There is continuing interest in Time Multiplexed Deep Silicon Etch (TMDSE) processes to enable the fabrication of MEMS devices as well as through wafer vias. Yet, current knowledge of these processes is not comprehensive and has often emerged from designed experiments conducted to create/control feature profiles. The presented research helps to fill some of the gaps in our understanding. Experiments were conducted to understand the mechanisms that function during the deposition and etch steps of TMDSE. In our deposition step studies, we first etched trenches of various aspect ratios and subsequently deposited a thick passivation layer using the standard deposition step settings of the TMDSE process. The characteristics of the deposited layers were found to be very instructive. Contrary to typical assumptions, the experiments and analysis indicate that the contribution of ions is much more critical than the contributions of neutral molecules. This leads to large deposition rates in regions where it is NOT wanted and tiny deposition rates in regions where it IS wanted/needed! We relate this to the progression of feature undercut. In our etch studies, we began with standard trenches again and examined either the results of an extended etch step, or the results of both an extended deposition and etch steps. The experimental evidence suggests that the etchant species at higher aspect ratios become something besides the commonly assumed atomic fluorine. It may be that the primary etchant becomes molecular fluorine. (The etch profile characteristics appear consistent with molecular fluorine.) Our analysis was facilitated by a feature scale model.

*Co-Authors are: I.R. Saraf, M.J. Goeckner. Special Thanks to K. Kirmse, B. Goodlin of Texas Instruments Inc. Acknowledgement: This material is based upon work supported in part by the SRC under award number 2008-KJ-1831.

Contributed Papers

8:30

HW2 2 Formation Mechanisms of Surface Roughening and Rippling during Plasma Etching and Sputtering of Silicon HIROTAKA TSUDA, YOSHINORI TAKAO, KOJI ERIGUCHI, KOUICHI ONO, *Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University* For the prediction of the atomic-scale surface roughness on feature bottom and sidewalls, we have developed our own three-dimensional atomic-scale cellular model (ASCeM-3D) and feature profile simulation. In this study, emphasis is placed on a better understanding of the formation mechanisms of nanoscale surface roughening and rippling during plasma etching and sputtering of Si with different ion incidence angles and ion incident energies. Numerical results indicated that surfaces are randomly roughened in the case of Cl_2 plasma etching for normal incidence of ions. For increased incident angles, ripples are formed perpendicular to the direction of ion incidence, while parallel to that of ion incidence for further increased incident angle. Numerical results also implied that the spatial dispersion of ion scattering and focusing on etched surfaces triggers the local difference in etch yield, and leads to the surface roughening and rippling during plasma etching and sputtering.

8:45

HW2 3 Ion Energy Distribution Control Using Ion Mass Ratios in Inductively Coupled Plasmas With a Pulsed DC Bias on the Substrate* MICHAEL D. LOGUE, MARK J. KUSHNER, *University of Michigan* In many applications requiring energetic ion bombardment, such as plasma etching, gas mixtures containing several ion species are used. In cases where two ions have significantly different masses, it may be feasible to selectively control the ion energy distributions (IEDs) by preferentially extracting the lighter ion mass with a controllable energy. In this work, we investigate the possibility of using a pulsed DC substrate bias in an inductively coupled plasma (ICP) to obtain this control. Pulsing of the substrate bias in the afterglow of a pulsed ICP plasma should allow for shifting of the IED peak energy by an amount approximately equal to the applied bias. If short enough pulses are used it may be possible to obtain a higher flux at high energy of the lower mass ion compared to the higher mass ion. A computational investigation of IEDs in low pressure (a few to 100 mTorr) ICPs sustained in gas mixtures such as Ar/H_2 or Xe/H_2(having large mass differences) was conducted as a proof of principle. The model is the Hybrid Plasma Equipment Model with which electron energy distributions (EEDs) and IEDs as a function of position and time are obtained using Monte Carlo simulations. We have found a selective ability to mass and energy discriminate ion fluxes when using sufficiently short bias pulses. Results from the model for plasmas densities, electron temperatures, EEDs and IEDs will be discussed.

*Work supported by DOE Office of Fusion Energy Science and Semiconductor Research Corp.

9:00

HW2 4 Multi-scale approach for simulation of deep silicon etching under ICP SF6/Ar plasma mixture* AMAND PATEAU, AHMED RHALLABI, MARIE CLAUDE FERNANDEZ, *Institut des Materiaux Jean Rouxel - University of Nantes* FABRICE ROQUETA, MOHAMED BOUFNICHEL, *ST Microelectronics Tours* PLASMAS ET COUCHES MINCES TEAM, ST MICROELECTRONICS TOURS TEAM Deep etching of silicon represents a new challenge in the silicon semi-conductor manufacturing. Indeed, deep silicon etching is used to form through-silicon vias and connect stacked dies or wafers in 3D integration. In this context, computer simulation of plasma etching can contribute to the optimization of the etching process. In this study, we have developed a silicon etching simulator under ICP SF6/Ar plasma discharge. Such model is composed of three modules permitting to predict the 2D etched silicon morphology versus the operating conditions: plasma kinetic model, sheath model and etching model. The plasma kinetic model is based on the 0D global approach which allows the calculation of the average densities and fluxes of neutral and ion species as well as the electron density and temperature versus the ICP machine parameters. Such output parameters are introduced as input parameters in the sheath model and silicon etching model. Cellular Monte-Carlo method is used to describe the plasma surface interactions in a probabilistic way for silicon etching trough the mask. The aim of this work is to validate the set of simulation and show the influence of some input parameters (Rf power, pressure, gas flow rate and bias voltage) on the etching processes.

*This work is supported by ST Microelectronics Tours - France.

9:15

HW2 5 Molecular Dynamics Analysis of Physical and Chemical Behavior of Etch Products Desorbed during Si Etching in Cl- and Br-based Plasmas NOBUYA NAKAZAKI, YOSHINORI TAKAO, KOJI ERIGUCHI, KOUICHI ONO, *Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University* Profile anomalies and surface roughness are critical issues to be resolved in plasma etching of nanometer-scale microelectronic devices, which in turn requires a better understanding of the effects of ion incident energy and angle on surface reaction kinetics. This paper presents a classical molecular dynamics (MD) simulation of Si etching by energetic Cl^+ and Br^+ ion beams with different incident energies (E_i = 20–300 eV) and angles (θ_i = 0–85°), and low-energy neutral Cl and Br radicals with different neutral radical-to-ion flux ratios (Γ_n/Γ_i = 0–100), where the improved Stillinger-Weber interatomic potential is used for Si/Cl and Si/Br systems. Emphasis is placed not only on the etch yield and stoichiometry, but also on the energy and angular distributions of etch products desorbed. Numerical results indicated that as Γ_n/Γ_i is increased at high $E_i > 100$ eV, the Si etch yield and the amount of products containing more halogen atoms increase, where the energy distribution of desorbed etch products peaks at lower energies. In addition, the desorption angle of etch products, which is measured from the surface normal on substrates, become slightly smaller with increasing Γ_n/Γ_i, which is more clearly observed in the case of oblique ion incidence.

SESSION HW3: HEAVY PARTICLE COLLISIONS

Wednesday Morning, 24 October 2012; Room: Classroom 202 at 8:00; Don Madison, Missouri University of Science and Technology, presiding

Invited Papers

8:00

HW3 1 Kinematically complete study on ion-impact induced ionization of laser-cooled lithium*

DANIEL FISCHER, *Max Planck Institute for Nuclear Physics, Heidelberg*

The study of atomic fragmentation processes due to charged particle impact provides insight in the dynamics of correlated few-particle Coulomb-systems, and thus advances our understanding of the fundamentally important few-body problem. In this respect, Fully differential data represent the most sensitive test of the theoretical treatment of the few-body dynamics. For ion-atom collisions such data became available exploiting the technique of "Reaction Microscopes." Here we report on the first operation of a new experimental tool, a MOTReMi, i.e. a Reaction Microscope equipped with a magneto-optically trapped target. This setup allows for the first time using lithium as a target for kinematically complete ion collision experiments. The lithium atom is particularly interesting for its simple, but at the same time asymmetric structure with one weakly bound outer shell electron and two strongly correlated K-shell electrons. In first experiments in the ion storage ring TSR at the MPIK in Heidelberg, for the first time initial state selective cross sections for ion impact ionization became available by means of optical excitation. Fully differential cross sections will be presented which reveal detailed information on interference and polarization effects in the scattering dynamics.

*Work done in collaboration with Natalia Ferreira, Johannes Goullon, Renate Hubele, and Aaron LaForge, Max Planck Institute for Nuclear Physics, Heidelberg; and Michael Schulz, Missouri University of Science & Technology, Rolla.

Contributed Papers

8:30

HW3 2 Strong multiple-capture effect in slow Ar^{17+}-Ar collisions: a quantum mechanical analysis* ARASH SALEHZADEH, TOM KIRCHNER, *Department of Physics and Astronomy, York University, Toronto, ON M3J 1P3, Canada* A recent X-ray spectroscopy experiment on 255 keV Ar^{17+}-Ar collisions [1] provided evidence for strong multiple-electron capture - a feature that is supported by classical trajectory Monte Carlo calculations for similar collision systems [2]. We have coupled a quantum-mechanical independent-electron model calculation for the Ar^{17+}-Ar system with (semi-) phenomenological Auger and radiative cascade models to test these findings. The capture calculations are performed using the basis generator method and include single-particle states on the projectile up to the 10th shell. The cross sections obtained for shell-specific multiple capture are fed into a stabilization scheme proposed in Ref. [3] in order to obtain n-specific cross sections for *apparent* single (and double) capture that in turn are fed into a radiative cascade code [1] to obtain X-ray emission intensities that can be compared with the experimental data. Good agreement is found for the Lyman series from $n = 3$ to $n = 7$ if the multiple-capture contributions are included, whereas calculations that ignore them are in stark conflict with the data.

*Supported by SHARCNET and NSERC/Canada.

[1]M. Trassinelli *et al.*, J. Phys. B **45**, 085202 (2012).
[2]S. Otranto and R. Olson, Phys. Rev. A **83**, 032710 (2011).
[3]R. Ali *et al.*, Phys. Rev. A **49**, 3586 (1994).

8:45

HW3 3 Application of Neural Networks to Atomic and Molecular Collisions* A.L. HARRIS, *Henderson State University* J.A. DARSEY, *University of Arkansas at Little Rock* Traditional methods of studying atomic and molecular collisions begin with the classical equations of motion for the particles involved in the system, or the Schrödinger equation. Both of these methods are clearly rooted in the physics of the collision, but they are often computationally difficult and require approximations in order to make the problem tractable. Unlike the traditional methods of studying collision processes, neural networks do not begin with the physics of the problem, but instead employ a semi-empirical method that recognizes patterns in data to make predictions about systems where data is unavailable. Neural networks have been successfully utilized in many different fields, but to our knowledge have never been applied to collision processes. While the premise of a neural network is not based in physics, its output can provide useful data for processes that may be too difficult experimentally or computationally to explore. We will present results from the NNETS neural network code for different collision systems and discuss what role neural networks may play in collision physics.

*This project was supported by grants from the National Center for Research Resources (5P20RR016460-11) and the National Institute of General Medical Sciences (8 P20 GM103429-11) from the National Institutes of Health.

9:00

HW3 4 STUDENT AWARD FINALIST: Projectile Coherence Effects in Single and Dissociative Electron Capture in Collision of Protons with H_2 and He* SACHIN SHARMA, *Missouri University of Science and Technology - Rolla* AHMAD HASAN, *UAE University - Abu Dhabi* KISRA EGODAPITIYA, THUSITHA ARTHANAYAKA, GIORGI SAKHELASHVILI, MICHAEL SCHULZ, *Missouri University of Science and Technology - Rolla* Recently, we have observed that interference effects, similar to optical Young double-slit interference, in the projectile scattering angle dependent ionization cross sections of H_2 by 75 keV proton impact are present or not depending on the projectile coherence. This suggests that atomic scattering cross sections in general are sensitive to the projectile coherence, an aspect which has been overlooked for decades. To investigate this effect further, we have measured differential cross sections for single and dissociative capture for 75 and 25 keV protons colliding with H_2 and He. A significant sensitivity of the cross sections to the projectile coherence was confirmed. For 25 keV we found that interference due to different impact parameters leading to the same scattering angle dominates over molecular two-center interference. This important observation sets the stage for resolving heatedly debated discrepancies between theory and experiment for ionization of He by 100 MeV/amu C^{6+} impact.

*Work supported by NSF.

9:15

HW3 5 Calculations for ion-impact induced ionization and fragmentation of water molecules* TOM KIRCHNER, MITSUKO MURAKAMI, MARKO HORBATSCH, *Department of Physics and Astronomy, York University, Toronto ON M3J 1P3, Canada* HANS JÜRGEN LÜDDE, *Institut fuer Theoretische Physik, Goethe-Universitaet, D-60438 Frankfurt, Germany* Charge-state correlated cross sections for single- and multiple-electron removal processes in proton-water-molecule collisions are calculated by using the non-perturbative basis generator method adapted for ion-molecule collisions [1,2]. A fragmentation model is then applied to calculate the yields of H_2O^+, OH^+, H^+, and O^+ ions emerging after H_2O^{q+} formation [3]. A detailed comparison is made with experimental data from three groups covering the energy range from 20–5000 keV. It is found that multiple electron processes with $q \leqslant 3$ play an important role at the lower end of this range and are calculated accurately within an independent particle model. We are currently completing the analogous analysis for He^+-H_2O collisions for which the presence of the projectile electron poses some additional challenges.

*Supported by SHARCNET and NSERC/Canada.

[1]H. J. Lüdde et al., Phys. Rev. A **80**, 060702(R) (2009).
[2]M. Murakami et al., Phys. Rev. A **85**, 052704 (2012).
[3]M. Murakami et al., Phys. Rev. A **85**, 052713 (2012).

SESSION JW1: GEC FOUNDATION TALK

Wednesday Morning, 24 October 2012; Room: Amphitheatre 204 at 10:00; Biswa Ganguly, Air Force Research Laboratory, presiding

Invited Papers

10:00

JW1 1 GEC Foundation Talk: Electron Collisions with Atoms, Ions, and Molecules: Experiment, Theory, and Applications*

KLAUS BARTSCHAT, *Drake University*

In recent years, much progress has been made in the study of electron collisions with various atomic and molecular species. This includes high-resolution benchmark experiments that cover large angular and energy ranges, highly sophisticated calculations that can provide accurate and extensive data sets, and the use of these data sets in realistic models of plasma discharges. The basic principles of frequently used experimental setups and computational methods will be reviewed, and the current state of the art will be illustrated with numerous examples.

*Work supported by the United States National Science Foundation under PHY-0903818 and PHY-1068140, and by the TeraGrid/XSEDE allocation TG-PHY090031.

SESSION LW1: NANOTECHNOLOGIES II

Wednesday Afternoon, 24 October 2012; Room: Amphitheatre 204 at 13:30; Steven Girshick, University of Minnesota, presiding

Invited Papers

13:30

LW1 1 Si-O-Cx nano-composite negative electrodes for next generation lithium ion batteries formed by plasma spray PVD*

MAKOTO KAMBARA, *The University of Tokyo*

Silicon is a promising material for negative electrode of lithium ion batteries (LIB) owing to its high theoretical capacity. However, this material inevitably suffers from huge volume change as large as 400% during charge/discharge process, i.e. alloying and de-alloying with lithium ions, which causes pulverization of the electrode itself and thus the loss of the electric path within the electrode, only after several charge cycles. Approaches to overcome this difficulty have been reported from the structural control point of views, such as design of materials at nanometer length scale, including nano-porous structure, nanowire structure and composites with other elements. Practically speaking, such a nano-structuring has to be also done by the process that has the potential to be developed to meet the industrial throughputs in future. With this in mind, we have demonstrated plasma spraying for production of the Si-Cx nano-composite powders and showed their potential as negative electrode by the reasonably high capacity and cycle stability. Another advantage of this process is that cheap raw materials, such as metallurgical Si (mg-Si), can be used as Si source so that industry compatible low cost is also anticipated. With these as background, we attempted plasma spraying with SiO powders as another Si source and the fundamental battery properties were characterized in comparison with the case with mg-Si powders. In brief, aggregate powders with 0.1-5μm in size having 20-50 nm a-SiO as the primary particle was produced by plasma spraying from 15μm feedstock SiO powders at the feeding rate of 2.4 g/min. Upon addition of CH4 gas, reduction and disproportionation reaction of SiO is promoted, leading to the formation of nano-composite a-SiOx particle with $<$10 nm Si at its core. The half coin cells with these powders as electrode have shown 1000 mAh/g after 50 cycles with reasonable retention efficiency of $>$99.7%.

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

Contributed Papers

14:00

LW1 2 Plasma Synthesis of Silicon Nanocrystals for Ligand-less Colloidal Stability LANCE WHEELER, UWE KORTSHAGEN, *University of Minnesota* Colloidal synthesis of prevailing semiconductor nanocrystals (NCs) requires long-chain organic ligands that provide steric stabilization. As these ligands hinder charge carrier transport when NCs are cast into thin films, significant efforts have focused on ligand exchange or removal schemes either in solution or during film assembly. Here we present a new mechanism to produce stable NC colloids without the need for any ligands. Silicon NCs are tailored in a gas phase plasma approach with a heterogeneous chlorine/hydrogen surface coverage to achieve an acidic surface. When the NCs are dispersed in solvents with hard donor groups, acid-base surface interactions induce stabilizing solvation layer around the NCs. In a set of experiments, electrostatic and steric stabilization are ruled out and evidence for the solvation layer formation is found. A set of criteria to achieve NC solvation is developed. Crack-free electronically coupled NC films are produced from these ligand-less NC colloids.

14:15

LW1 3 Impacts of plasma fluctuation on growth of nanoparticles in low pressure reactive VHF discharge plasmas* MASAHARU SHIRATANI, KUNIHIRO KAMATAKI, YASUO MORITA, HYUNWOONG SEO, NAHO ITAGAKI, GIICHIRO UCHIDA, KAZUNORI KOGA, *Kyushu University* Here we discuss impacts of plasma fluctuation on nanostructure formation using plasmas. We studied the effects of plasma fluctuation on the growth of nanoparticles in capacitively-coupled VHF discharges with amplitude modulation (AM) using 2 dimensional laser light scattering method [1]. AM gives an artificial plasma fluctuation. Nanoparticles grow more slowly for higher AM levels, which causes the density of nanoparticles to increase by 100%, their size to decrease by 23%, and narrower size dispersion. The increase in the nucleation density of nanoparticles by AM causes a decrease in the radical flux to a nanoparticle. Eventually we obtained a diagram of the three particle growth modes of positive feedback, negative feedback, and independent ones. We also have developed a simple theory of particle growth in reactive plasmas. The theory predicts experimental results well. Our approach can be applied to realize precise control of a wide variety of nanostructure formations.

*Work supported by MEXT.

[1]K. Kamataki *et al.*, J. Inst. 7, C04017 (2012).

14:30

LW1 4 The production of magnetic nanoparticles of Iron Oxide by Arc Discharge in Acetone HAMID REZA YOUSEFI, SARA FATHOLLAH, MARYAM NIKEYN, SHOHREH KHATAMI, *Plasma Physics Research Center, Science and Research Branch, Islamic Aazd University, Tehran, Iran* In the recent years, researchers star t to see applications of nanoparticles. Iron - based nanoparticles can have useful magnetic and catalytic properties. Magnetic nanoparticles are gaining importance because of their wide range of application in high-density magnetic recording, magnetic fluids, medicine, sensors and actuator. In this study, magnetic iron oxide nanoparticles were produced by Arc Discharge method in acetone solution. The X-Ray Diffraction (XRD) pattern, Scanning Electron Microscopy (SEM) and Spectrophotometer have been showed that magnetic iron oxide nanoparticles (Fe_2O_3, Fe_3O_4 and a little iron carbide) were produced at the temperature over 40 Degree. This investigation consists of two parts. First, dependencies of the particle structure and size distribution were studied. In the second part of the experiment, size and number density of these magnetic nanoparticles were changed with changing the time and the gap between two electrodes. The result showed, the number of magnetic nanoparticles change by a different period of time and the size of magnetic nanoparticles change by different gap between two electrode in Arc Discharge system.

14:45

LW1 5 The Synthesis of Fe3O4 Magnetic Nanoparticles by Laser Ablation in Organic Solvents BEHJAT SADAT KARIMAN, HAMID REZA YOUSEFI, *Plasma physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran* MOJTABA (FARZIN) AGHAMIR, *Physics of Department, University of Tehran, Iran* The emphasize of this paper is on the synthesis, protection and application of magnetic nanoparticles. The size and shape control of magnetic nanoparticles has been made by Laser ablation method. In this method, Nd:Yag Laser (1064 nm) was used for ablation. While a number of suitable methods have been developed for the synthesis of magnetic nanoparticles, successful Technique for synthesis of magnetic nanoparticles is the laser ablation because it does not require expensive chemicals as chemistry technique and has been produced large-scale magnetic nanoparticles. Moreover, this method has been successfully applied to metals. By the laser Nd:Yag (1064 nm) in different organic solvents such as: Ethanol, Acetone and Toluene, synthesis of Iron-based the nanoparticles was investigated. In addition, regarding the protection against corrosion is a vital issue, one material for coatings such as Au were used. Structural analysis carried out by scanning electron microscopy, transmission electron microscopy, spectrophotometer and XRD revealed that various solvents and coatings have dramatic influences on both the dimension and the nanostructures of nanoparticles.

SESSION LW2: BASIC PLASMA PHYSICS PHENOMENA IN LOW-TEMPERATURE PLASMAS
Wednesday Afternoon, 24 October 2012
Room: Classroom 203 at 13:30
Yevgeny Raitses, Princeton Plasma Physics Laboratory, presiding

Contributed Papers

13:30

LW2 1 STUDENT AWARD FINALIST: Control of Electron Energy Distributions Through Interaction of Electron Beams and the Bulk in Capacitively Coupled Plasmas* SANG-HEON SONG, MARK J. KUSHNER, *University of Michigan* The control of electron energy distributions, $f(\varepsilon)$, in capacitively coupled plasmas is necessary to optimize the fluxes of reactive species to the substrate. Beams of electrons >100s eV are produced by secondary electron emission and acceleration through the sheaths. These beams occur from the rf biasing or can be augmented with an additional dc bias. Although the beam electrons mostly collide with the gas, collisions with bulk electrons also occur. Previous work investigated beam-Langmuir wave interactions that may transfer energy to the bulk electrons [1]. In this paper, we report on a computational investigation of the purely kinetic interaction between the beam and bulk through electron-electron (e-e) collisions, and the consequences on $f(\varepsilon)$. A CCP with and without dc augmentation was investigated with a 2-d plasma hydrodynamics model including an electron Monte Carlo simulation with e-e collisions. Secondary electrons are produced by ion and electron impact on surfaces. The beam electrons collide with low energy bulk electrons, delivering energy to the bulk and depleting the beam, and can shape the $f(\varepsilon)$ in ways not otherwise attainable in self-sustained rf equilibrium plasmas. We will discuss shaping of $f(\varepsilon)$ and changes in plasma properties through the beam-bulk interactions, and use of a dc bias to control $f(\varepsilon)$.

*Work supported by the DOE Office of Fusion Energy Science and Semiconductor Research Corp.

[1]L. Xu *et al.*, Appl. Phys. Lett. **93**, 261052 (2008).

13:45
LW2 2 The Maxwell Demon and its instabilities* CHI-SHUNG YIP, J.P. SHEEHAN, UMAIR SUDDIQUI, NOAH HERSHKOWITZ, *Dept. of Engineering Physics, University of Wisconsin, Madison, Wisconsin 53706* GREG SEVERN, *Dept. of Physics, Unversity of San Diego, San Diego, CA, 92110* Previous experiments have shown that in a low pressure, low temperature plasma, positively biasing an array of thin wires can increase electron temperature. This works, it is thought, by creating an angular momentum trap to absorb cold electrons. In this experiment, such a Maxwell demon device was reproduced by welding 0.025mm tungsten wires onto stainless steel shafts, which were coated with a ceramic coating. However, we found that the effect of such device is identical to a plate with the same total surface area. These devices was used to more than double the plasma electron temperatures in a multi-dipole chamber operating in the mTorr regime. Moreover, the demon is observed to reduce the cold electron population in a plasma with a bi-Maxwellian electron distribution, leaving a single Maxwellian electron distribution. In addition, at high positive voltage, relaxation instabilities in the kHz range occured, as MacKenzie *et al.*, had observed. The instability was determined to be pulsing anode spots, and the measurement of time-resolved plasma parameters in this instability was achieved by using a slow sweeping Langmuir probe. Relaxation time of the instability was modeled by a production-lost balanced method.

*Work supported by NSF grant nos. CBET-0903832 and CBET-0903783, DOE grant nos. DE-FG02-97ER54437, DE-FG02-03ER54728, DE-FG02- 06ER54845, DE-AC52-07NA27344, DE-FG02-05ER54809, and DE-FG02-07ER54917.

14:00
LW2 3 2D fluid simulations of acoustic waves in pulsed ICP discharges: Comparison with experiments EMILIE DESPIAU-PUJO, GILLES CUNGE, NADER SADEGHI, *CNRS/UJF-Grenoble1/CEA LTM* N. ST. J. BRAITHWAITE, *The Open University* Neutral depletion, which is mostly caused by gas heating under typical material processing conditions, is an important phenomenon in high-density plasmas. In low pressure pulsed discharges, experiments show that additional depletion due to electron pressure (Pe) may have a non-negligible influence on radical transport [1]. To evaluate this effect, comparisons between 2D fluid simulations and measurements of gas convection in Ar/Cl2 pulsed ICP plasmas are reported. In the afterglow, Pe drops rapidly by electron cooling which generates a neutral pressure gradient between the plasma bulk and the reactor walls. This in turn forces the cold surrounding gas to move rapidly towards the center, thus launching an acoustic wave in the reactor. Time-resolved measurements of atoms drift velocity and gas temperature by LIF and LAS in the early afterglow are consistent with gas drifting at acoustic wave velocity followed by rapid gas cooling. Similar results are predicted by the model. The ion flux at the reactor walls is also shown to oscillate in phase with the acoustic wave due to ion-neutral friction forces. Finally, during plasma ignition, experiments show opposite phenomena when Pe rises.

[1]Cunge *et al.*, APL **96**, 131501 (2010).

14:15
LW2 4 Head-on Collision of Two Solitary Waves in a Plasma RAVINDER KUMAR, *Janta Vedic College Baraut, Uttar Pradesh* AJAY K. SINGH, *Dronacharya College of Engineering Farrukhnagar, Haryana* OMVEER SINGH, HITENDRA K. MALIK, RAJ P. DAHIYA, *Indian Institute of Technology Delhi* Solitary waves have been very fascinating due to their applications in various fields of science and engineering. A solitary wave when retains its shaper after having collision with another solitary wave is called a soliton. The soliton structure can trap particles and convect them over large distances in the laboratory, astrophysical and space related plasmas. Therefore, they can contribute to the transportation of anomalous particles and the energy from one region to another. The aim of the present work is to investigate the head-on collision of two solitary waves in a multi-component plasma having ions, two types of electrons and dust grains under the effect of magnetic field and charge fluctuation of the dust grains. Using extended Poincare-Lighthill-Kuo (PLK) method, we derive a coupled equation that carries the contribution of oppositely propagating solitary waves and their phase relationship. By solving this coupled equation, we obtain the trajectory of both the solitary waves and finally calculate the phase shift taken place during their head-on collision.

14:30
LW2 5 Oscillations of current in dc discharge induced by an auxiliary electrode IRINA SCHWEIGERT, *Institute of Theoretical and Applied Mechanics, Institytskaya 4/1, Novosibirsk, 630090 Russia* VLADIMIR DEMIDOV, *West Virginia University, Morgantown, WV 26506, USA* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA* The plasma parameters of dc discharge with thermionic emission cathode can be actively controlled by addition of the second anode made as a diaphragm with a hole in the center (see for example, [1]). This control is based on fundamental property of nonlocal electron kinetics and can be beneficial for variety of applications. We simulated parameters of this dc discharge plasma making use of two-dimensional PIC MCC code. The geometry of device and plasma parameters are taken from Ref. [1]. The dc discharge operates in helium at gas pressure 0.5 – 4 Torr and is supported by the thermionic emission of electrons from cathode. The inter-electrode distance is 1.1 cm and the diaphragm is placed at distance 0.1 – 0.15 cm from anode. The discharge current ranges from 0.05A to 0.3A. The plasma characteristics, potential, electron and ion density profiles and EEDF are studied for different current densities, gas pressures and radius of diaphragm hole. The presence of the diaphragm leads to increased ionization only for a certain range of gas pressures and the radii of diaphragm hole. An increase of a size of diaphragm hole leads to development of current oscillations.

[1]V. I. Demidov, C. A. DeJoseph, Jr., and V. Ya. Simonov, Appl. Phys. Lett. **91**, 201503 (2007).

14:45

LW2 6 Excitation of Ion Acoustic Waves by Electron Beams I.D. KAGANOVICH, *Princeton Plasma Physics Laboratory* D. SYDORENKO, *University of Alberta* E. TOKLUOGLU, E.A. STARTSEV, A.V. KHRABROV, *Princeton Plasma Physics Laboratory* L. CHEN, P. VENTZEK, R. SUNDARARAJAN, *Tokyo Electron America* A. RANJAN, K. KUMAR, *Tokyo Electron Technology Center America* The interaction of an electron beam with plasma is of particular importance for hybrid DC/RF coupled plasma sources used in plasma processing. A high frequency (HF) electron plasma wave resonant with the high-energy beam may decay into another HF wave and an ion acoustic wave. The new HF wave may have lower phase speed than the original HF wave. Electron acceleration by the slower HF wave may explain the low-energy peak in the electron energy distribution function measured in plasma processing devices [1]. In the present paper, the collisionless electron heating in a hybrid RF-DC plasma source is studied using the particle-in-cell code EDIPIC [2,3]. In simulation, electrons emitted from the cathode surface are accelerated through a dc bias electric field and form an 800 eV electron beam entering the bulk plasma. The beam excites electron plasma waves through the two-stream instability. High localized plasmon pressure creates ion acoustic waves in the process similar to the modulation instability. Eventually, coupling between electron plasma waves and ion acoustic waves deteriorates HF oscillations, which leads to bursting behavior.

[1]L. Chen, Proceedings of ICRP 2010
[2]D. Sydorenko, Phys. Plasmas **14**, 013508 (2007).
[3]D. Sydorenko, Phys. Rev. Lett. **103**, 145004 (2009).

SESSION LW3: PLASMA PROPULSION I
Wednesday Afternoon, 24 October 2012
Room: Classroom 202 at 13:30
Rod Boswell, Australian National University, presiding

Contributed Papers

13:30

LW3 1 A continuous dual ion beam formed by successive acceleration of positive and negative ions* ANE AANESLAND, LARA POPELIER, DENIS RENAUD, PASCAL CHABERT, *CNRS - Ecole Polytechnique* The distinctive feature of the PEGASES thruster is that both positive and negative ions are accelerated to provide thrust such that an additional neutralization system is redundant; the accelerated product provides the space charge and current neutralization of the beam. The first proof-of concept of the alternate acceleration has recently been achieved. The ions are accelerated from an ion-ion plasma by a set of grids where the grid in contact with the plasma is biased with square voltage waveforms with frequencies in the kHz range and voltages less ±500 V. Time resolved measurements show that the positive and negative ions are extracted at the positive and negative bias period, respectively, producing a continuous beam of ions. For positive ions, the beam energy corresponds to the sum of the applied acceleration voltage and the plasma potential. For negative ions, the beam energy is lower than the applied voltage and depends on the applied bias frequency. The effects of the voltage waveform and the grid surface condition on the resulting beams are discussed.

*We are grateful for the expert technical assistance by J. Guillon and J.H. Andriamijorosoa. This work is funded by the EADS Astrium and the ANR EPIC project ANR-11-BS09-040.

13:45

LW3 2 Implementation of a polytropic model for two-dimensional hybrid Hall thruster simulations EUNSUN CHA, *Stanford University* EDUARDO FERNANDEZ, *Eckerd College* MARK CAPPELLI, *Stanford University* A polytropic model for Hall discharge simulations is developed and tested against data for a laboratory Hall thruster. 2-D hybrid particle-in-cell (PIC) simulations, widely used to describe plasma properties of Hall thrusters, solve the electron energy equation for electron temperature requiring electron mobility as a specified parameter. Motivated by experiments that suggest a simpler polytropic relation between the electron density and electron temperature, we have adopted a 2-D hybrid-PIC to use this relationship as a means of relaxing the need to specify the electron mobility. By removing the usual ad-hoc assumptions of the form of the electron mobility, the polytropic model, if transportable to other operating conditions and Hall thruster designs, can be a powerful performance estimator and optimization tool. In this presentation, we discuss the implementation of this model and early results.

14:00

LW3 3 Experimental Assessment of Plasma Transport in a 16-cm Multicusp Device AIMEE HUBBLE, JOHN FOSTER, *University of Michigan* The physics of plasma transport from the bulk plasma through the magnetic cusp to the anode remains poorly understood. A proper accounting of plasma losses to the anode is critical to accurate modeling of multicusp device performance. In this work, plasma transport in a 16-cm multicusp discharge chamber was studied. Each ring was covered with an electrically isolated electrode, which enables the direct measurement of current to each individual ring as well as the discharge chamber wall. A translatable Langmuir probe was used to obtain maps of spatially resolved plasma parameters in bulk plasma region. These maps of spatially resolved plasma density, electron temperature, and plasma potential were compared to current collection at the cusps as well as the magnetic circuit and device performance. Ring electrode measurements coupled with spatially resolved plasma parameter measurements throughout the discharge chamber allow for an assessment of plasma losses to each ring in terms of an "effective loss area" which, multiplied by electron current density incident on the bulk/cusp boundary, gives the correct collected current to each ring. A relationship between effective loss area and the physical loss area was determined that can be applied to a 0-D particle and energy balance model.

14:15

LW3 4 Electron Transport via Collisional Mechanisms in a Cusped Plasma Ion Accelerator* CHRISTOPHER YOUNG, MARK CAPPELLI, *Stanford University Plasma Physics Laboratory* A plasma accelerator with applications to low power space propulsion (below 200 W) is experimentally and computationally investigated. Such devices efficiently ionize propellant by trapping electrons between strong adjacent magnetic cusps. Electron transport and ionization processes in this class of plasma accelerator are still poorly understood. A numerical model built around experimental plasma potential measurements of the device is presented, in which single test electron trajectories are traced throughout the simulation domain. A mixture of classical and anomalous collisional processes (respectively linked to the local neutral propellant density and magnetic field strength - Bohm diffusion) is required to recover the behavior observed in laboratory experiments.

*The authors acknowledge support from the Air Force Office of Scientific Research (AFOSR). CY acknowledges support from the DOE NNSA Stewardship Science Graduate Fellowship under contract DE-FC52-08NA28752.

14:30

LW3 5 Time evolution of the EEDF in the plasma plume of a Hall thruster* STEPHANE MAZOUFFRE, KAETHE DANNENMAYER, *ICARE - CNRS, Orleans, France* PAVEL KUDRNA, MILAN TICHY, *Charles University, Prague, Czech Republic* A Hall thruster (HT) is one type of electric engine currently in use onboard geosynchronous satellites and scientific space probes. In a HT, the electric field at the origin of ion acceleration is generated in a low-pressure magnetized discharge in cross-field configuration. As no grid are employed for beam formation, such a thruster is not current limited and a relatively large thrust, in comparison with gridded ion engines, is achieved, which makes this technology of great interest for orbit transfer maneuvers and deep-space exploration missions. One important issue in the field of electric propulsion is the interaction between the host spacecraft and the plasma plume. Up to now, a large amount of studies has been performed on ion flow properties. Recently we carried out time-averaged measurements of the electron properties in a HT plume by means of Langmuir probe. The goal was to provide accurate data for validation of plume numerical simulations. Nevertheless, as the discharge of a HT is highly non stationary, it appeared necessary to turn to time-resolved measurements. In this contribution we present measurements of the time-varying EEDF at a microsecond time-scale in the plasma plume of two HTs of different sizes and power levels.

*Works have been performed in the frame of a CNRS/CNES/ Snecma/Universities joint-program.

SESSION MW1: HIGH PRESSURE DISCHARGES I

Wednesday Afternoon, 24 October 2012; Room: Amphitheatre 204 at 15:30; Patrick Pedrow, Washington State University, presiding

Invited Papers

15:30

MW1 1 Extremely far from equilibrium: the multiscale dynamics of streamers

UTE EBERT,* *CWI Amsterdam and Eindhoven Univ. Techn., The Netherlands*

Streamers can emerge when high voltages are applied to gases. At their tips, the electric field is strongly enhanced, and electron energies locally reach distributions very far from equilibrium, with long tails at high energies. These exotic electron energies create radiation and chemical excitations at very low energy input, as the gas stays cold while the ionization front passes. Applications are multiple: highly efficient O* radical production in air for disinfection, combustion gas cleaning, plasma assisted combustion, plasma bullets in medicine etc. In that sense, streamers can be considered as very efficient converters of pulsed electric into chemical energy, in particular, if the electric circuits are optimized for the application. Streamers are also ubiquitous in nature, e.g., in the streamer corona of lightning leaders, in sprite discharges high above the clouds; and streamers also seem to contribute to generating gamma-ray flashes and even to electron-positron beams in active thunderstorms. Unravelling the intrinsic mechanisms of streamers is challenging: they can move with up to one tenth of the speed of light, and they have an intricate nonlinear structure with a hierarchy of scales. I will review how theory and experiment deal with these structures, and I will discuss the basic differences between positive and negative streamers, electron acceleration at streamer tips and the consecutive radiation and chemical reactions, the propagation mechanism of positive streamers in different gases, streamer velocities and diameters varying over at least two orders of magnitude, streamer branching and interaction, and their three-dimensional tree structure. Both theory and experiment work with a patchwork of methods, and geophysics can provide movies that cannot be taken in the lab. I will sketch the state and outline open questions.

*http://www.cwi.nl/~ebert.

Contributed Papers

16:00

MW1 2 Simulation of the propagation and reignition of atmospheric pressure air discharges behind a dielectric plane obstacle* FRANCOIS PECHEREAU, JAROSLAV JANSKY, ANNE BOURDON, *Laboratory EM2C, Ecole Centrale Paris, Grande voie des vignes, 92295 Chatenay Malabry Cedex* In recent years, experimental studies on flue gas treatment have demonstrated the efficiency of plasma assisted catalysis for the treatment of a wide range of pollutants at a low energetic cost. In plasma reactors, usual catalyst supports are pellets, monoliths or porous media, and then atmospheric pressure discharges have to interact with many obstacles and to propagate in microcavities and pores. As a first step to better understand atmospheric pressure discharge dynamics in these complex geometries, in this work, we have carried out numerical simulations using a 2D-axisymmetric fluid model for a point-to-plane discharge with a dielectric plane obstacle placed in the path of the discharge. First, we have simulated the discharge ignition at the point electrode, its propagation in the gap and its impact and expansion on the dielectric plane. Depending on the applied voltage, the dielectric plane geometry and permittivity, we have identified conditions for the reignition of a second discharge behind the plane obstacle. These conditions will be discussed and compared with recent experimental results on the same configuration.

*The authors thank the Agence Nationale de la Recherche for its support of the ALVEOPLAS project (Grant No. ANR-08-BLAN-0159-01).

16:15

MW1 3 Measurement of ozone production scaling in a helium plasma jet with oxygen admixture BRIAN SANDS, *UES,* *Inc. (AFRL)* BISWA GANGULY, *Air Force Research Laboratory* Capillary dielectric barrier plasma jet devices that generate confined streamer-like discharges along a rare gas flow can produce significant quantities of reactive oxygen species with average input powers ranging from 100 mW to >1 W. We have measured spatially-resolved ozone production in a He plasma jet with O_2 admixture concentrations up to 5% using absorption spectroscopy of the O_3 Hartley band system. A 20-ns risetime, 10-13 kV positive unipolar voltage pulse train was used to power the discharge, with pulse repetition rates varied from 1-20 kHz. The discharge was operated in a transient glow mode to scale the input power by adjusting the gap width between the anode and downstream cathodic plane. Peak ozone number densities in the range of 10^{16} - 10^{17} cm^{-3} were measured. At a given voltage, the density of ozone increased monotonically up to 3% O_2 admixture (6 mm gap) as the peak discharge current decreased by an order of magnitude. Ozone production increased with distance from the capillary, consistent with observations by other groups. Atomic oxygen production inferred from O-atom 777 nm emission intensity did not scale with ozone as the input power was increased. The spatial distribution of ozone and scaling with input power will be presented.

16:30

MW1 4 How Can The Arrival Of A Pulsed Streamer At One Side Of A Thin Dielectric Ignite A Secondary Streamer On The Other Side? TOM FIELD, *Queen's University Belfast* QAIS AL-GWARI, *University of Mosul* COLM O'NEILL, *Queen's University Belfast* DEBORAH O'CONNELL, *University of York* BILL GRAHAM, *Queen's University Belfast* The interaction of pulsed streamers with thin dielectric materials has been investigated. The streamers were generated in an atmospheric pressure pulsed dielectric barrier helium discharge. A thin dielectric material was introduced into the path of the streamers so that the surface of the dielectric was perpendicular to the path of the streamer. Under favourable conditions, shortly after a streamer reached the dielectric barrier a similar secondary streamer was ignited on the other side of the dielectric. The secondary streamer continued in the same direction as the initial streamer moving away from the dielectric with a velocity which was perpendicular to its surface. This secondary streamer generation has been investigated with various different dielectric materials. The mechanism by which the secondary streamer is ignited will be discussed.

16:45

MW1 5 High order fluid model for streamer discharges* ARAM MARKOSYAN, SASA DUJKO, *Centrum Wiskunde and Informatica, Amsterdam* RONALD WHITE, *ARC Centre for Antimatter-Matter Studies, Australia* JANNIS TEUNISSEN, UTE EBERT, *Centrum Wiskunde and Informatica, Amsterdam* We present a high order fluid model for streamer discharges. Using momentum transfer theory, the fluid equations are obtained as velocity moments of the Boltzmann equation. We solve Poisson equation to obtain space charge electric field. The high order tensors from the energy flux equation are specified in terms of low order moments to close the system. The average collision frequencies for momentum and energy transfer in elastic and inelastic collisions required as an input in high order fluid model of streamers in molecular nitrogen are calculated using a multi term Boltzmann equation solution. The results of simulations are compared with those obtained by a PIC/MC method and by the classical first order fluid model based on the drift-diffusion and local field approximation. The comparison clearly validates the high order fluid model, while the first order fluid model underestimates many aspects of streamer dynamics. Two important issues are discussed on the basis of fundamental kinetic theory developed in the past decade: (1) the correct implementation of transport data in fluid models of streamer discharges; (2) the accuracy of two term approximation for solving Boltzmann's equation in the context of streamer studies.

*Work supported by STW-project 10751.

17:00

MW1 6 STUDENT AWARD FINALIST: Simulation of the ignition of a H2-air mixture at atmospheric pressure by a nanosecond repetitively pulsed discharge* FABIEN THOLIN, ANNE BOURDON, *Laboratory EM2C, Ecole Centrale Paris, Grande Voie des Vignes, 92295, Chatenay-Malabry, France* Nanosecond repetitively Pulsed Discharges (NRPD) have a great potential for many applications at atmospheric pressure due to their ability to produce efficiently many reactive chemical species at a low energy cost. Recent measurements have shown that in the "spark" regime of NRP discharges, an ultra-fast local heating of the gas could be obtained. This effect is of great interest for applications as flow control and plasma assisted combustion (PAC). In this work, we have carried out 2D numerical simulations of the coupling of the NRP discharge in air at atmospheric pressure in a point-point geometry with the background air. In particular, we have simulated shock waves generated by the NRPD in the spark regime and we have compared our results with experiments. Then, we have studied the production of active species by the NRP discharge in the spark regime. Finally, for plasma assisted combustion applications, we have simulated the ignition of a flame kernel in a lean H2-air mixture by a spark NRPD. Based on this work, the relative importance for the combustion ignition of gas heating and production of active species by the spark NRP is discussed.

*The authors thank the Agence Nationale de la Recherche for its support of the Project ANR PLASMAFLAME (Grant No. ANR2011BS0902501).

17:15

MW1 7 Match Design for VHF Atmospheric Plasmas* BRANDON BYRNS, STEVEN SHANNON, *North Carolina State University* Atmospheric pressure discharges driven at very high frequencies have demonstrated the potential for unique heating modes and plasma formation in a wide range of gases at high pressure. One of the challenges in designing these systems is the matching network needed to couple power from the generator to the discharge. In this talk, we present matching network design considerations for VHF atmospheric plasmas including tune space, stability, and efficiency. We will present both modeled and experimental data from a source driven at 162MHz at 1atm pressure using a plurality of gasses including air, N_2, CO_2, He, and Ar. These cases will be used to demonstrate the interaction of the matching system with the plasma load, and how this can influence plasma conditions at specific process set points.

*Work supported by the State of North Carolina and by a generous gift donation from Advanced Energy Incorporated.

SESSION MW2: NEGATIVE ION AND DUST PARTICLE CONTAINING PLASMAS

Wednesday Afternoon, 24 October 2012; Room: Classroom 203 at 15:30; Ane Aanesland, LPP Ecole Polytechnique/CNRS, presiding

Invited Papers

15:30

MW2 1 Large and powerful rf-driven hydrogen plasmas: negative ions for the heating systems of ITER
URSEL FANTZ, *Max-Planck-Institut für Plasmaphysik*

Negative ion sources are an excellent example for the manifold of applications of low temperature plasmas which ranges from basic research to industrial applications. One of the outstanding application areas is in fusion, where a large and powerful negative hydrogen ion source is as a central component of the neutral beam injection systems for heating and current drive of the international fusion project ITER. The challenge to extract an ion current of 57 A (D) and 69 A (H) from a low temperature hydrogen plasma at low pressure (0.3 Pa) is accompanied by the challenge to accelerate the beam to 1 MeV. Large RF sources with the size of a door operating at a power of up to 800 kW must deliver a uniform and stable negative hydrogen ion current density higher than 200 A/m^2 over the total area for one hour. Simultaneously, the amount of co-extracted electrons should be kept below one in order to avoid severe damages of the extraction system. These requirements can be met only by combining the disciplines of low temperature plasma physics, plasma surface interaction, ion beam optics, beam physics, and mechanical and electrical engineering. The state of the art and prospects of the negative hydrogen ion source development will be discussed with emphasis on the physical aspects.

Contributed Papers

16:00

MW2 2 Nanoparticle-Plasma Interactions in Dusty Argon-Hydrogen Plasmas UWE KORTSHAGEN, MEENAKSHI MAMUNURU, *Department of Mechanical Engineering, University of Minnesota* We studied the role of hydrogen in altering the plasma-nanoparticle interactions in low pressure dusty Ar-H_2 plasma. Most dusty plasmas in which particles form through chemical nucleation, are multi-component plasmas containing hydrogen. As hydrogen's ionization potential is close to that of argon, both gases may be ionized. The presence of the light mass hydrogen ions has the potential to modify the plasma and plasma-nanoparticle interactions. We developed a global model for dusty argon-hydrogen plasma. For given absorbed power, nanoparticle density, pressure, and chamber size, we solved the power balance, plasma species balance, and particle current balance equations. We included a system of rate equations for important argon-hydrogen plasma chemical reactions and obtained electron energy distribution function (EEDF) using ZDPlasKin. A trace amount of H_2 gas in Ar discharge causes Ar^+, ArH^+, and H_3^+ to be the dominant ions. Their relative densities are dependent on chamber pressure, gas composition, and the nanoparticle density. Increase in H_2 gas fraction reduces the plasma density. The presence of light ions reduces the average particle charge. Electron collisions with hydrogen and with the nanoparticles affect the EEDF shape. Overall, we find that the presence of H_2 in the discharge significantly alters the plasma properties and the fundamental plasma-nanoparticle interactions. This work was supported by the US Dept. of Energy Plasma Science Center and DOE grant DE/SC-0002391.

16:15

MW2 3 Plasma Crystallization of Silicon Nanoparticles* REBECCA ANTHONY, NICOLAAS KRAMER, *Department of Mechanical Engineering, University of Minnesota* ERAY AYDIL, *Department of Chemical Engineering and Materials Science, University of Minnesota* UWE KORTSHAGEN, *Department of Mechanical Engineering, University of Minnesota* Using nonthermal plasmas for synthesis of silicon nanocrystals is well-established. However, nanoparticle heating in the plasma, which leads to particle crystallinity, is poorly understood. The mechanism behind heating of these particles has only been studied through modeling. In-situ measurement of particle temperature during plasma processes is difficult, but particles themselves can serve as thermometers, as their crystallinity will change depending on heating in the plasma. Here we investigate the heating and crystallization of nanoparticles using a double-plasma configuration, examining both the particles and the plasma. Amorphous silicon nanoparticles are formed in a low-power plasma, then injected into a separate plasma which is operated with variable power. Nanoparticle characterization confirms that crystallization of the particles occurs at a threshold power to the secondary plasma, around 30W (nominal) for 5nm particles. Optical emission spectroscopy on the plasma provides estimates of the electron temperature during nanoparticle crystallization, and capacitive probe measurements reveal ion densities at varying plasma powers. We will compare our outcomes to previous modeling results to build a complete picture of nanoparticle heating in plasmas.

*This work is supported by the DOE Plasma Science Center and DOE grant DE/SC-0002391.

16:30

MW2 4 Numerical Modeling of an RF Argon-Silane Plasma with Dust Particle Nucleation and Growth* STEVEN GIRSHICK, PULKIT AGARWAL, *Department of Mechanical Engineering, University of Minnesota* We have developed a 1-D numerical model of an RF argon-silane plasma in which dust particles nucleate and grow. This model self-consistently couples a plasma module, a chemistry module and an aerosol module. The plasma module solves population balance equations for electrons and ions, the electron energy equation under the assumption of a Maxwellian velocity distribution, and Poisson's equation for the electric field. The chemistry module treats silane dissociation and reactions of silicon hydrides containing up to two silicon atoms. The aerosol module uses a sectional method to model particle size and charge distributions. The nucleation rate is equated to the rates of formation of anions containing two Si atoms, and a heterogeneous reaction model is used to model particle surface growth. Aerosol effects considered include particle charging, coagulation, and particle transport by neutral drag, ion drag, electric force, gravity and

Brownian diffusion. Simulation results are shown for the case of a 13.56 MHz plasma at a pressure of 13 Pa and applied RF voltage of 100 V (amplitude), with flow through a showerhead electrode. These results show the strong coupling between the plasma and the spatiotemporal evolution of the nanoparticle cloud.

*Partially supported by the U.S. National Science Foundation (grant CHE-1124752), U.S. Department of Energy Office of Fusion Energy Science (grant DE-SC0001939), and the Minnesota Supercomputing Institute (MSI).

16:45

MW2 5 Soliton Reflection in a Magnetized Cold Plasma having Dust Grains and Trapped Electrons HITENDRA K. MALIK, OMVEER SINGH, RAJ P. DAHIYA, *Indian Institute of Techology Delhi* A solitary wave is said to be a soliton if it retains its shape after collision with another solitary wave. The solitons get reflected from a boundary or the density gradient present in the plasma. In the present work, the reflection of a soliton is studied in a magnetized cold plasma having dust grains and trapped electrons. Considering the density inhomogeneity in the plasma, we derive relevant modified Korteweg-deVries (mKdV) equations for the right and left going solitary waves and then after coupling these equations at the point of reflection we solve the coupled equation for obtaining the expression for the reflection coefficient based on which the soliton reflection is examined under the effect of magnetic field, dust grain density, and the temperature of trapped electrons. Specifically the role of trapped electrons and dust grains is uncovered for the excitation of solitary waves and their reflection.

17:00

MW2 6 Effects of impurities on negative ion mobility in O_2 YUI OKUYAMA, SUSUMU SUZUKI, HARUO ITOH, *Chiba Institute of Technology* We have investigated the effects of impurities on the negative ion mobility in O_2 at atmospheric pressure using a high-pressure ion drift tube with a positive point plate gap that acts as a negative ion detector. We reported a reduced mobility, in particular "zero field mobility" of 2.31 $cm^2/V \cdot s$ for O_2^- in O_2.* This value is in good agreement with values in other reports of 1.95 to 2.42 $cm^2/V \cdot s$. Although many studies have been carried on the measurement of negative ion mobility over the last 50 years, discrepancies between the values obtained remain and the origin of the discrepancies has not been clarified until now. We found that one of the reasons for the discrepancies originates from impurities in O_2 that are considered to be released from the surface of the chamber as an absorbed gas (N_2 or CO_2) or to already exist in the O_2. These impurities form negative ions such as CO_3^-, CO_4^-, NO_3^- and $N_2O_2^-$ with the O_2 in the chamber. The mobilities of these ions are slightly larger than that of O_2^-. Therefore, if small amounts of impurities such as N_2 and CO_2 exist in O_2, an increased negative ion mobility is observed at $E/N > 2.54\times10^{-1}$ Td. Moreover, the negative ion mobility of O_2^- was also measured in high-purity O_2(99.9999%) and ultrahigh-purity O_2(99.99995%) while employing a gas filter that can reduce the water content to less than 100 ppt. As a result, the mobility of O_2^- was increased to 2.39 $cm^2/V \cdot s$. This value is close to the values reported by Dutton and Howells (J. Phys. B, 1, 1160, '68), Rees (Aust. J. Phys., 18, 41, '65) and Voshall *et al.*, (J. Chem. Phys., 43, 1190, '65).

*Y. Okuyama *et al.*, J. Phys. D: Appl. Phys. 45, 195202 (2012).

17:15

MW2 7 STUDENT AWARD FINALIST: Measurements of Positive and Negative Energy Distribution Function obtained from a Langmuir probe in an ion-ion plasma* JEROME BREDIN, PASCAL CHABERT, ANE AANESLAND, *Laboratoire de Physique des Plasmas (LPP), Ecole Polytechnique/CNRS, Route de Saclay, 91128 Palaiseau, France* An ion-ion plasma, created downstream of a magnetic barrier, has been studied with a Langmuir probe. In classical electron-ion plasmas the second derivative of the I-V characteristic below the plasma potential can be used to deduce the electron energy distribution function (EEDF). In nearly electron-free ion-ion plasmas, we propose to use the second derivative to deduce both the electrons and the ion (positive and negative) EDFs. Below the plasma potential, the second derivative involves two distributions; the negative ions at low energy and the electrons, which are in very small quantity, at high energy. Above the plasma potential, the second derivative analysis leads to the positive ion distribution. The exact procedure to analyze the data will be detailed during the presentation. We found that downstream of the magnetic barrier, where the ion-ion plasma forms, ion temperatures are fairly high, from 0.5 eV to 0.1 eV. The temperature of the positive ions is slightly higher than that of the negative ions. The ion densities can also be deduced from the I-V characteristic and they are in the order of 10^{17} m^{-3}, that is almost three order of magnitude higher than the electron density in this region of the plasma.

*We are grateful for the expert technical assistance by J. Guillon and M. Baudier. This work is part of the PEGASES project funded by EADS Astrium and the EPIC-ANR blanc project ANR-11-BS09-040.

WEDNESDAY AFTERNOON \ MW3

SESSION MW3: COLLISIONS WITH BIOMOLECULES

Wednesday Afternoon, 24 October 2012; Room: Classroom 202 at 15:30; Michael Brunger, Flinders University, presiding

Invited Papers

15:30

MW3 1 Low energy electron interactions with complex biological targets

THOMAS ORLANDO, *Georgia Institute of Technology*

The low energy (1–25 eV) electron-induced damage of DNA oligomers have been examined both theoretically and experimentally. Specifically, elastic scattering of 5–30 eV electrons within B-DNA 5′-CCGGCGCCGG-3′ and A-DNA 5′-CGCGAATTCGCG-3′ sequences has been calculated using the separable representation of a free-space electron propagator and a curved wave multiple scattering formalism. The disorder brought about by the surrounding water and helical base stacking leads to featureless amplitude build-up of elastically scattered electrons on the sugars and phosphate groups for all energies between 5–30 eV. However, some constructive interference features arising from diffraction were revealed when examining the structural waters within the major groove. We correlated these scattering features with measured DNA single and double strand breaks. Compound resonance states involving interfacial water and excitation energies >5 eV seem to be required for lethal double strand breaks. We have recently extended this work to excitation energies below 5 eV by examining the damage using Raman-microscopy and scanning electrostatic force microscopy. Very efficient damage via single strand breaks is observed below 5 eV excitation energies. This involves π^* negative ion resonances that are initially localized on the bases but transferred to the σ^* states of the sugar-phosphate bond. The efficacies of these channels depend upon the base-pair sequences as well as the presence of water.

Contributed Papers

16:00

MW3 2 Elastic Scattering and Vibrational Excitation of Tetrahydrofuran by Low Energy Electrons* DANNY ORTON, ALEXSANDER GAUF, AMOS JO, JOSHUA TANNER, MURTADHA A. KHAKOO, *California State University, Fullerton, CA, USA* TODD WALLS, *California High School, Whittier, CA, USA* CARL WINSTEAD, VINCENT MCKOY, *California Institute of Technology, Pasadena, CA, USA* We report experimental and theoretical (Schwinger Multi-Channel method with polarization effects) differential cross-sections (DCS) for low energy elastic electron scattering from tetrahydrofuran. The data are for incident energies from 0.75 to 30eV and the experimental scattering angles range from 10° to 130°. Agreement between theory and experiment is very good across the range of this data. Comparisons with previous experiments is also very good in general. We will also report DCSs for vibrational excitation of this target for energies up to 15eV and similar scattering angles.

*Funded by NSF Grants RUI-PHY 0653452 and PHY 0653396.

16:15

MW3 3 Triple differential cross section for electron impact ionization of molecules – Pyrimidine ($C_4H_4N_2$), Tetrahydrofurfuryl alcohol ($C_5H_{10}O_2$) and Tetrahydropyran ($C_5H_{10}O$)* HARI CHALUVADI, DON MADISON, *Missouri University of Science and Technology* J.D. BUILTH - WILLIAMS, S.M. BELLM, D.B. JONES, M.J. BRUNGER, *ARC Centre of Excellence for Antimatter-Matter Studies* C.G. NING, *Tsinghua University* B. LOHMANN, *University of the Sunshine Coast* JAMES COLGAN, *Los Alamos National Laboratory* Cross-section data for electron impact induced ionization of bio-molecules are important for modeling the deposition of energy within a biological medium and also for gaining knowledge of electron driven processes at the molecular level. Triply differential cross sections have been measured for the electron impact ionization of HOMO ($7b_2$) and $10a_1$ orbitals of Pyrimidine, HOMO (28a) orbital of tetrahydrofurfuryl alcohol, and HOMO (15AA) orbital Tetrahydropyran by using the (e, 2e) technique. The experimental measurements will be compared with theoretical M3DW (molecular 3-body distorted wave) model calculations.

*Work supported by NSF under grant number PHY-1068237.

16:30

MW3 4 Dissociative electron attachment to triflates* SYLWIA PTASINSKA, *University of Notre Dame* DAVID GSCHLIESSER, PETER BARTL, *Innsbruck University* IRENEUSZ IANIK, *University of Notre Dame* PAUL SCHEIER, STEPHAN DENIFL, *Innsbruck University* It is known that understanding of chemical transformations induced by low energy electrons reacting with photoresist components is crucial for effective design of chemically amplified resists in modern lithography. Therefore in present work gas phase studies on dissociative electron attachment to simple alkyl ($CF_3SO_3CH_3$) and aryl ($C_6H_5SO_3CF_3$ and $CF_3SO_3C_6H_4CH_3$) triflates were carried out. The fragmentation pathways under electron impact below 10 eV were identified by means of crossed electron-molecular beam mass spectrometry. Several reaction channels were observed upon an electron capture by the studied compounds, involving single or multiple bond cleavages or intramolecular rearrangement. Three main dissociation channels were observed that are C-O, S-O or C-S bond breakage in the triflate moiety leading to the formation of triflate (OTf), triflyl (Tf) or sulfonate (RSO_3) anions, respectively. The results of this work can be helpful at later stage in the improvement of the image quality in post optical lithography processes.

*This research was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Basic Energy Sciences, Office of Science, United States Department of Energy through grant number DE-FC02-04ER15533.

Invited Papers

16:45

MW3 5 Transient Anion States of Biomolecules*
MARCIO VARELLA, *University of Sao Paulo*

Much of the interest on electron interactions with biomolecules is related to radiation damage [Gohlke and Illenberger, Europhys. News **33**, 207 (2002)]. The high energy photons employed in radiology and radiotherapy generate a large number of fast electrons in living cells. These electrons thermalize in a picosecond scale, eventually forming dissociative matestable anions with water and biomolecules. In this work, we employ the parallel version of Schwinger Multichannel Method with Pseudopotentials [Bettega *et al.*, Phys. Rev. A **47**, 1111 (1993); Santos *et al.*, J. Phys. Chem. **136**, 084307 (2012)] to investigate transient anion states of protein and nucleic acid precursors. We address glycine in both neutral and zwitterionic forms, as well as glycine-water clusters and disulfide bonds. The interest on the two forms of glycine (and other amino acids) relies on the fact that only the neutral form is stable in the gas phase, while the zwitterion is more stable in solution, pointing out limitations of standard gas-phase studies. Electron attachment to disulfide bonds also has potential impact on protein stability. Finally we address transient anion states of substituted uracil molecules in the gas phase.

*Financial Support from the Brazilian agencies FAPESP, CNPq and the University of Sao Paulo (USP).

[1]In collaboration with M. H. F. Bettega, S. d'A. Sanchez, R. F. da Costa, M. A. P. Lima, J. S. dos Santos, and F. Kossoski.

SESSION NW1: POSTER SESSION I (7:00-9:30PM)
Wednesday Evening, 24 October 2012
Exhibit Salon CDE at 19:00

NW1 1 ATOMIC AND MOLECULAR PROCESSES

NW1 2 Comparison of spherical and spheroidal expansions for energies and oscillator strengths of H_2^+ JEREMY SAVAGE, DMITRY FURSA, MARK ZAMMIT, IGOR BRAY, *Curtin University* We calculate the bound state energies and oscillator strengths of the hydrogen molecule ion using configuration interaction expansions in both spherical and prolate spheroidal coordinates. States were built from similar Laguerre bases in the fixed nuclei approximation, allowing for the direct comparison of convergence rates and accuracy. Such a comparison will demonstrate the relative usefulness of spherical and spheroidal expansions for scattering on diatomic molecules. Specifically, this will assist in the implementation of the convergent close-coupling approach to scattering which is optimised by a smaller, more efficient set of configurations. It will be shown that the spheroidal basis is significantly faster to converge and more accurate for the low-lying states but this advantage gradually dissipates as state energy increases and the orbitals become more spherical.

NW1 3 Electron Scattering from Pyrazine compared with Pyrimidine and Benzene* P.D. PALIHAWADANA, J.P. SULLIVAN, S.J. BUCKMAN, *The Australian National University, Canberra, Australia* M.J. BRUNGER, *Flinders University, Adelaide, Australia* C. WINSTEAD, V. MCKOY, *Caltech, CA, USA* G. GARCIA, *CSIC, Madrid, Spain* F. BLANCO, *Universidad Complutense de Madrid, Madrid, Spain* Pyrazine ($C_4H_4N_2$) is a model molecule for studying electron interactions with nucleases. Also pyrazine is an ideal target, due to its high symmetry (D_{2h}), for theoreticians to investigate electron collisions with complex DNA/RNA bases. In this work we present absolute elastic differential cross sections and elastic excitation functions for scattering of low-energy electrons by pyrazine measured using a crossed electron-target beam apparatus at the Australian National University. A comparison is also made between pyrazine cross sections with previously measured pyrimidine and benzene cross sections. Since all those molecules are similar in structure and considered as analogues to nucleobases, we intend to discuss similarities and differences in electron scattering results between three molecules.

*This work was supported by the Australian Research Council.

NW1 4 Comparison of ion-molecule reactions in cyclohexane, methylcyclohexane and ethylcyclohexane* CHARLES JIAO, *UES* STEVEN ADAMS, *Air Force Research Laboratory* Cyclohexanes including cyclohexane (C_6H_{12}), methylcyclohexane (C_7H_{14}) and ethylcyclohexane (C_8H_{16}) are significant components of many practical fuels. C_6H_{12} and C_7H_{14} have been chosen as representative cycloalkanes in several proposed surrogate mixtures for jet fuels. In this study, the gas-phase ion-molecule reactions in these three cyclohexanes are examined, and comparison of the reaction channels in each of the cyclohexanes are made. A variety of reaction channels has been observed, which include charge transfer, H^- transfer, H_2^- transfer, H_3^- transfer, hydrocarbon anion transfer, and association with concerted fragmentation. Among these channels, H^- transfer is the most prevalent in the three cyclohexanes and, for many reactant ions, is the exclusive channel. Also observed is that H_3^- transfer occurs only in C_6H_{12} while $C_3H_7^-$ transfer occurs only in C_8H_{16}.

*The authors thank the Propulsion Directorate AFRL and the Air Force Office of Scientific Research for their support.

NW1 5 Electron Impact Excitation and Ionization of Neon* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* We have further developed the *B*-Spline *R*-matrix (BSR) code [1] to allow for a large number of pseudo-states in the close-coupling expansion. In the present work, the BSRMPS approach [2] was employed to perform semi-relativistic (Breit-Pauli) close-coupling calculations for elastic scattering, excitation, and ionization of neon from both the ground state and the metastable excited states. Coupling to the ionization continuum through the pseudo-states is important for low-energy elastic scattering (to represent polarizability effects), for excitation in the "intermediate" energy regime of about 1–5 times the ionization potential, and to allow for the calculation of ionization processes by transforming the results obtained for excitation of the positive-energy pseudo-states. The current results represent a significant extension of our earlier near-threshold work [3] and previous non-relativistic RMPS calculations [4,5].

*Work supported by the United States National Science Foundation under PHY-0903818 and PHY-1068140, and by the TeraGrid/XSEDE allocation TG-PHY090031.

[1]O. Zatsarinny, Comp. Phys. Commun. **174**, 273 (2006).
[2]O. Zatsarinny and K. Bartschat, Phys. Rev. Lett. **107**, 023203 (2011).
[3]O. Zatsarinny and K. Bartschat, J. Phys. B **37**, 2173 (2004).
[4]C. P. Ballance and D. C. Griffin, J. Phys. B **37**, 2943 (2004).
[5]C. P. Ballance *et al.*, J. Phys. B **37**, 4779 (2004).

NW1 6 Relativistic convergent close-coupling calculation of the spin polarization of electrons scattered from indium* CHRISTOPHER BOSTOCK, DMITRY FURSA, IGOR BRAY, *Curtin University* The measurements of the spin asymmetry parameter (Sherman function) for elastic and inelastic electron-indium scattering by Bartsch– *et al.* [J. Phys. B 25(1992)1511 are compared with corresponding relativistic convergent close-coupling calculations. The RCCC results provide the first theoretical data to span the full range of energies (1–14 eV) and transitions measured by Bartsch *et al.* The spin asymmetry parameter is presented for $(5p)^2P^o_{1/2} \rightarrow (5p)^2P^o_{1/2}$ elastic scattering, $(5p)^2P^o_{1/2} \rightarrow (5p)^2P^o_{3/2}$, $(5p)^2P^o_{1/2} \rightarrow (6s)^2S_{1/2}$, and $(5p)^2P^o_{3/2} \rightarrow (6s)^2S_{1/2}$ inelastic transitions. There is very good agreement between theory and experiment for the elastic spin asymmetries. Some discrepancies still exist between theory and experiment for excited state spin asymmetries.

*Supported by the Australian Research Council.

NW1 7 Electronic excitation of methanol by low energy electrons JOSHUA TANNER, LEIGH HARGREAVES, MURTADHA KHAKOO, *California State University Fullerton* Measurement of absolute differential and integral cross sections for the lowest lying electronically excited states of methanol will be presented. These cross sections were measured using a crossed electron gas beam spectrometer incorporating a moveable gas beam. The data were normalized against the elastic scattering signal, with the elastic cross sections previously determined in our laboratory [1] using the relative flow method with an aperture-type gas collimator [2]. These data are, to the best of the author's knowledge, the first reported study of these cross sections and have important implications for dosimetry modeling of radiation therapy.

[1]M. A. Khakoo *et al.*, Phys. Rev. A **77**, 042705 (2008).
[2]M. A. Khakoo *et al.*, J. Phys. B: At. Mol. Phys. **40**, 3601 (2007).

NW1 8 Progress towards an optically pumped electron spin filter MUNIR PIRBHAI, PAUL BURROW, *University of Nebraska - Lincoln* DALE TUPA, *Los Alamos National Laboratory* TIMOTHY GAY, *University of Nebraska - Lincoln* Polarized electron beams are an indispensable probe of spin-dependent phenomena in fields of atomic and molecular physics, magnetic materials and biophysics. While their uses have become widespread, the sources producing them remain technically complex. The standard gallium arsenide (GaAs) polarized electron emitters require stringent conditions such as ultrahigh vacuum systems, and challenging activation procedures to operate. Therefore, we are actively seeking alternatives to the GaAs photocathodes. One option involves the production of polarized electron beams by spin exchange collisions with oriented rubidium vapor. We have built a prototype using this principle, and at present, it supplies half microampere of electron current with about 12% polarization. We are currently investigating and will be reporting on the effects of the drift velocity of the initially unpolarized electrons, the rubidium density and the optical pumping scheme used to orient the alkali vapor on the electron beam polarization.

NW1 9 Generalized Hyperspherical Sturmian functions applied to three-body ionization problems* LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* DARIO M. MITNIK, *IAFE and Universidad de Buenos Aires, Argentina* GUSTAVO GASANEO, *Universidad Nacional del Sur, Bahia Blanca, Argentina* Very recently we introduced a methodology to solve three-body break-up problems based on hyperspherical Generalized Sturmian Functions (HGSF) [1]. The use of hyperspherical coordinates makes easier and more natural the incorporation of Peterkop's asymptotic behavior for ionization processes. This technique is an extension of the Generalized Sturmian method implemented before in spherical coordinates [2]. In this report we address different issues involved in the study of single and double ionization of atoms by electron impact, in particular with respect to the so called (e,2e) and (e,3e) processes. For example, we analyze the physical characteristics of different spatial regions of the scattering wave function and the extraction of transition amplitudes.

*This work has been developed within the activities planned in the French-Argentinian programme ECOS-Sud A10E01.

[1]G. Gasaneo and L. U. Ancarani, J. Phys. A **45**, 045304 (2012).
[2]A. L. Frapiccini, J. M. Randazzo, G. Gasaneo, and F. D. Colavecchia, J. Phys. B **43**, 101001 (2010).

NW1 10 Low energy studies (e,2e) studies from Ammonia (NH_3)* HARI CHALUVADI, DON MADISON, *Missouri University of Science and Technology* K.L. NIXON, ANDREW J. MURRAY, *University of Manchester* CHUANGANG NING, *Tsinghua University* JAMES COLGAN, *Los Alamos National Laboratory* Experimental and theoretical Triply Differential Cross Sections (TDCS) will be presented for electron-impact ionization of Ammonia (NH_3) for highest occupied molecular orbital (HOMO), next highest occupied molecular orbital (NHOMO) and next next highest occupied molecular orbital (N^2HOMO). M3DW (molecular 3-body distorted wave) results will be compared with experiment for coplanar geometry. The final state electron energies and observation angles are symmetric.

*Work supported by NSF under grant number PHY-1068237.

NW1 11 High Energy Proton-Impact Single Electron Capture from Helium* K. MORRISON, A.L. HARRIS, *Henderson State University* In single electron capture, the incident proton collides with a helium atom, captures an electron, and leaves the collision as a neutral hydrogen atom. This process has been studied experimentally and theoretically for decades, but recent advancements in experimental technology now allow for more accurate and detailed measurements. Experimental fully differential cross sections are now available for high projectile energies and large scattering angles, and there is a newly-seen peak at the large scattering angles. We will present results from a fully quantum mechanical 4-body model and compare with experiment.

*Work supported by the Arkansas Space Grant Consortium.

NW1 12 Experimental measurement of plasma parameters and electron energy distribution in ferrite-core side type Ar/He inductively coupled plasma DUKSUN HAN, JIN-YOUNG BANG, HYO-CHANG LEE, CHIN-WOOK CHUNG, *Hanyang University* Spatial distributions of a plasma density and an effective electron temperature (Teff) were studied from the measurement of an electron energy probability function (EEPF) in the side type ferrite-core inductively coupled plasma with an argon-helium mixture. As the helium gas was diluted at the fixed total gas pressure of 5 mTorr in an argon discharge, the distribution of the plasma density was changed from a concave to a flat, and finally became a convex, while all spatial profiles of Teff were the hollow shapes with the helium dilution. This evolution of the plasma uniformity with the helium gas could be explained by the increased energy relaxation length and the changed plasma potential, indicating the transition of the electron kinetics from the local to non-local kinetics. From this result, it is expected that the addition of helium gas could be applied as a method to control the plasma uniformity in a large area plasma processing.

NW1 13 Spatial plasma potentials and electron energy distributions in inductively and capacitively coupled plasmas under a weakly collisional and nonlocal electron kinetic regime HYO-CHANG LEE, CHIN-WOOK CHUNG, *Hanyang University* Spatial profiles of the plasma potential and electron energy distribution function (EEDF) were measured in inductively and capacitively coupled plasmas (ICP and CCP) under weakly collisional and nonlocal electron kinetic regimes [1]. The measured EEDF at the discharge center was a bi-Maxwellain distribution with low (T_1) and high (T_2) electron temperature groups at both the ICP and the CCP, while the EEDF at the radial boundary was closely Maxwellian distribution in the ICP due to cutting of the low energy electrons by relatively large ambipolar potential in this discharge regime. The ambipolar potential in the entire radial region was in the scale of T_{eff} -1.5 T_{eff}, where T_{eff} is the effective electron temperature. At the boundary region with the ion mean free path scale, the ambipolar potential increased abruptly and was about $T_{eff,edge}/2$, where the Teff,edge is the effective electron temperature at the boundary,

WEDNESDAY EVENING \ NW1

which corresponds to the presheath scale. These results of the ICP, which are contrary to the ambipolar potential of the CCP in a nearly free-fall regime [2], are caused by relatively high T_1 and a small portion of low energy electron group density to total electron density in the ICP under the weakly collisional and nonlocal electron kinetic regimes.

[1] H. C. Lee and C. W. Chung, Phys. Plasmas **19**, 033514 (2012).
[2] V. A. Godyak, V. P. Meytlis, and H. R. Strauss, IEEE Trans. Plasma Sci. **23**, 728 (1995).

NW1 14 Momentum transfer cross sections for the heavy noble gases A.D. STAUFFER, *York University, Toronto, Canada* R.P. MCEACHRAN, *ANU, Canberra, Australia* We have used our relativistic optical potential method [1] to calculate the momentum transfer cross sections for Ar, Kr and Xe from threshold to 1000 eV. The target ground state as well as the open excited and ionization channels used in the optical potential have been calculated using the MCDF program [2]. We have included 17 excitation channels for Ar, 26 for Kr and 15 for Xe. In the ionization channels, ionization of the outer p, s and d shells were included for Kr and Xe while for Ar all electrons were allowed to be ionized. Comparisons with previous calculations and experimental measurements will be included. We also include analytic fits to our cross sections to aid in plasma modelling studies.

[1] S. Chen, R. P. McEachran, and A. D. Stauffer, J. Phys. B **41**, 025201 (2008).
[2] I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, and N. C. Pyper, Comput. Phys. Commun. **21**, 207 (1980).

NW1 15 Positron scattering off the H_2^+ and H_2 molecules using the convergent close-coupling method* MARK ZAMMIT, JEREMY SAVAGE, DMITRY FURSA, IGOR BRAY, *Curtin University* We have extended a single center formulation of the convergent close-coupling (CCC) method for modeling positron-atom collisions [1] to positron scattering from diatomic molecules. CCC calculations have been applied to positron scattering off the H_2^+ and H_2 molecules. A single center approach to the calculation of molecular structure was utilised by diagonalizing the target Hamiltonian in a large Sturmian (Laguerre) basis. Such expansions allow us to model positronium formation channels indirectly. A fixed nuclei formulation was used to obtain electronic excitation and total cross sections, which are compared with available experimental and theoretical data. In the near future we will generalize this work to electron and photon scattering off molecules.

*Supported by the Australian Research Council.

[1] D. V. Fursa and I. Bray, New J. Phys. **14**, 035002 (2012).

NW1 16 Positron Reaction Microscope* DENNIS MUELLER, SIMON ARMITAGE, CORBIN VERMET, CHISTOPHER LEE, *University of North Texas* ALEXANDER DORN, *Max-Planck-Institut für Kernphysik Heidelberg* STEPHEN BUCKMAN, JAMES SULLIVAN, *The Australian National University* UNIVERSITY OF NORTH TEXAS COLLABORATION, MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG COLLABORATION, THE AUSTRALIAN NATIONAL UNIVERSITY COLLABORATION We are developing a positron reaction microscope to measure kinematically complete ionization reactions of atoms and dissociative ionization of simple molecules by positron impact. The experiment is designed to use the slow positron beamline at the ARC Centre for Antimatter Matter Studies (CAMS) node at the Australian National University (ANU). This project is a collaboration among the University of North Texas, CAMS, and the Max Planck Insitute for Kern Phyzik in Heidelberg. Initial measurements and apparatus calibration will be performed using electrons. For positron measurements, the apparatus will be rolled into position on the slow positron beamline at the CAMS site at ANU.

*National Science Foundation.

NW1 17 Positron scattering from helium* ROISIN BOADLE, JOSHUA MACHACEK, EMMA ANDERSON, PETER CARADONNA, CASTEN MAKOCHEKANWA, ADRIC JONES, JAMES SULLIVAN, STEPHEN BUCKMAN, *CAMS, Australian National University, Canberra* We present new measurements of positron scattering cross sections for helium, including total scattering, total elastic and total inelastic cross sections, which have been extended up to energies of 180 eV. We also present a range of low energy elastic differential cross sections. The measurements were performed using our high-resolution, Surko trap-based positron beamline with a typical energy resolution of ~50 meV. Comparisons will be made with previous experimental results and with up to date theoretical predictions.

*This work is supported by the ARC.

NW1 18 Low Energy Positron Scattering from Molecular Hydrogen* EMMA ANDERSON, ROISIN BOADLE, JOSHUA MACHACEK, CASTEN MAKOCHEKANWA, *CAMS, Australian National University, Canberra* DENNIS MUELLER, *University of North Texas, Denton* JAMES SULLIVAN, STEPHEN BUCKMAN, *CAMS, Australian National University, Canberra* As the simplest homonuclear diatomic molecule, molecular hydrogen is an attractive target for fundamental measurements of positron interactions, and comparisons of these measurements with the best contemporary scattering theory. Using a low-energy, high-resolution positron beam, measurements have been taken of positron scattering from molecular hydrogen between 1 and 200 eV. Total scattering, total elastic scattering, and positronium formation cross sections will be presented, as will as a range of elastic differential cross sections. Comparisons will be made with previous positron and electron scattering measurements and theoretical calculations.

*This work is supported by the ARC.

NW1 19 Positron scattering from tetrahydrofuran* M.J. BRUNGER, L. CHIARI, *CAMS, Flinders University, Adelaide, Australia* W. TATTERSALL, *CAMS, James Cook University, Townsville, Australia* E. ANDERSON, J. MACHACEK, C. MAKOCHEKANWA, J. SULLIVAN, S.J. BUCKMAN, *CAMS, Australian National University, Canberra, Australia* We present recent experimental results for positron scattering from tetrahydrofuran. Being a model for the deoxyribose sugar rings in the nucleic acids backbone, tetrahydrofuran is of particular interest for investigating radiation damage in biomolecular systems. The measurements on this species were carried out using the atomic and molecular trap-based positron beamline at The Australian National University with an energy resolution of ~60 meV. Total cross sections and integral cross sections for the positronium formation, elastic and inelastic (direct ionization and electronic excitation) scattering channels are presented over the energy range of 1–190 eV. Low-energy elastic differential cross sections are also presented at selected energies between 1 eV and 25 eV. A fairly good agreement is found with the total cross section results from the only existing previous experimental investigation on this target species by the Trento group.

*This work was supported by the ARC.

NW1 20 Low Energy Elastic Electron Scattering from Acetaldehyde* ALEXSANDER GAUF, GEORGE BALCH, CHRISTOPHER NAVARRO, LEIGH R. HARGREAVES, MURTADHA A. KHAKOO, *California State University Fullerton* CARL WINSTEAD, VINCENT MCKOY, *California Institute of Technology, California* We report experimental and theoretical (Schwinger Multi-Channel method, with polarization effects) for electron scattering from acetaldehyde. The incident energies range from 1eV to 30eV and scattering angles from 10 to 130°. The experimental method used a moveable aperture source with the relative flow method. Comparisons between theory and experiment will be presented.

*Funded by NSF Grants RUI-PHY 0653452 and PHY 0653396.

NW1 21 PLASMA APPLICATIONS

NW1 22 Method to reduce particles and defects on unprocessed wafers caused by clusterization and cross contamination from processed wafers SANKET SANT, *Lam Research Corporation* One of the leading problems in the semiconductor industry with device scaling is defects and particles. Of this the most important ones are particles that can clusterize (condensate) with exposure to atmosphere. These clusters can be formed by residual halides or halide structures on the wafer surface reacting with surface moisture which is unavoidable. Such clusters can prove detrimental to the processed wafer, but more interestingly can migrate inside the FOUP onto unetched wafers. This migration of clusters can cause micro masking and other defects when these wafers are processed. This reduces the wafer yield and is challenging to resolve as we move towards smaller nodes. In this work, different methods of eliminating cross condensation defects and avoiding cluster formation on processed wafers are discussed. UV, Ozone and heat are the primary candidates explored and the mechanism behind each method is explored and optimized. Impact of each mechanism on wafer yield, part corrosion in a reactor platform and wafer throughput has been studied.

NW1 23 Plasma-liquid system with rotational gliding arc with liquid electrode OLEG NEDYBALIUK, VALERIY CHERNYAK, EUGENE MARTYSH, *Taras Shevchenko National University of Kyiv* NATALIA BELENOK, *National Technical University of Ukraine "Kyiv Polytechnic Institute"* TAMARA LISITCHENKO, *Taras Shevchenko National University of Kyiv* Atmospheric pressure plasmas can be created by various types of discharges: transverse arc; discharge in gas channel with liquid wall and others. But most of them aren't sufficiently stable. Stabilization of discharge in the high pressure powerful plasmatron is attained by vortex flow of gas. In the low-powered high pressure discharges the reverse vortex flow "tornado" type can be used for the space stabilization. The voltage-current characteristics of discharge at the different regimes are measured. Typical emission spectra of plasma in plasma-liquid system with rotational gliding arc were measured. The population temperatures of excited electronic, vibrational, rotational levels and the flame temperature are determined.

NW1 24 Amplification of femtosecond vacuum ultraviolet laser pulses at 126 nm in an optical-field-induced ionized argon plasma* SHOICHI KUBODERA, MASANORI KAKU, *Dept. of EEE and Photon Science Center, University of Miyazaki* MASAHITO KATTO, *CRC, University of Miyazaki* KENZO MIYAZAKI, *IAE, Kyoto University* Short-wavelength lasers in the vacuum ultraviolet (VUV) spectral region between 100 and 200 nm have not yet been developed to the same degree as visible and infrared lasers. We have been developing the argon excimer laser at 126 nm by using an optical-field-induced ionized (OFI) argon plasma. We have observed the gain of 0.86 /cm at 126 nm in the OFI Ar plasma, which was produced inside a hollow fiber with a diameter of 250 microns and a length of 5 cm. In this paper, we have used the OFI plasma gain medium as an amplifier of the 126 nm radiation. A femtosecond 126 nm pulse was produced by the seventh-order nonlinear wavelength conversion of a femtosecond Ti:sapphire laser at 882 nm. The femtosecond wavelength-converted coherent VUV beam was then injected inside the OFI plasma that was produced by the same Ti:sapphire laser, resulting in a 2.4-fold increase of the VUV intensity with one-pass amplification. The gain-length product of 0.87 with the one-pass amplification was evaluated, which was consistent with the value we have observed in the previous measurements. The further extension of the OFI plasma by using a hollow fiber would be plausible to increase the gain-length product and the VUV amplified intensity.

*Part of this work has been supported by Hamamatsu Photonics K. K., Japan.

NW1 25 Modelling of microwave-driven micro-plasmas in HCPCF* L.L. ALVES, *IPFN/IST-UTL, Portugal* O. LEROY, C. BOISSE-LAPORTE, P. LEPRINCE, *LPGP-UPS/CNRS, France* B. DEBORD, F. GEROME, R. JAMIER, F. BENABID, *GPPMM/XLIM, CNRS-UNILIM, France* New UV sources based on microwave-driven micro-plasmas filling a Hollow-Core Photonic Crystal Fibre (HCPCF) [1], exhibit an unprecedented compactness, flexibility, low-cost and high conversion efficiency. The micro-plasma ($>10^{14}$ cm^{-3} electron density, estimated by electromagnetic calculations) is produced by a surface-wave discharge (2.45 GHz frequency) in argon, at 1000–1400 K gas temperatures (measured by OES diagnostics). Our first approach to simulate this system replaces the cladding structure of the fibre (air-holes region) by a capillary cylindrical quartz tube. Simulations use a one-dimensional (radial) stationary model that solves the fluid transport equations for electrons and positive ions, the electron mean energy transport equations, Poisson's and Maxwell's equations for the fields and the gas energy balance equation, coupled to the electron Boltzmann equation for the calculation of the relevant electron parameters [2,3]. We analyze the modification of the plasma with changes in the work conditions, presenting simulations for various HCPCF core radii (50–500 μm) and electron densities (1–5x10^{14} cm^{-3}), at 1 mbar pressure.

*Work partially supported by ANR and DGA (ASTRID-2011-UVfactor) and by FCT (Pest-OE/SADG/LA0010/2011).

[1]B. Debord *et al.*, ECOC conference Mo.2.LeCervin.5. (2011).
[2]L. L. Alves *et al.*, Phys. Rev. E **79**, 016403 (2009).
[3]J. Gregório *et al.*, Plasma Sources Sci. Technol. **21**, 015013 (2012).

NW1 26 Tailoring the Emission Spectra of Xenon Flashlamps* ZHONGMIN XIONG, NATALIA YU. BABAEVA, MARK J. KUSHNER, *University of Michigan* The emission spectra of flashlamps for pumping lasers or photolysis should ideally be tailored to match the bands of the absorbing medium. Flashlamps are typically filled with xenon at fill pressures of 300–700 Torr with small admixtures of other rare gases. In this paper, results from a computational investigation of the operating characteristics of xenon flashlamps (e.g., current, voltage, emission spectrum) will be described. The low-current optical spectra dominated by line emission and high-current spectra dominated by continuum emission produced primarily by recombination and Bremsstrahlung radiation will be discussed. We show that during the initial stage of the discharge pulse, the emission spectrum is dominated by line emission. After the first few hundred microseconds, the spectrum is dominated by continuum emission. Line emission is broadend by Stark effects from an increasing density of electrons. Tailoring of the emission spectra of the flashlamp is achieved by integrating over time the line and continuum phases of emission by choice of pulse power waveform. The model used in this work, *nonPDPSIM*, is a plasma hydrodynamics model in which continuity, momentum and energy equations are solved for charged and neutral species with solution of Poisson's equation for the electric potential. Algorithms were developed to represent radiation transport for line and continuum components of the spectrum using Monte Carlo techniques.

*Work supported by Sandia National Laboratory.

NW1 27 Interconnection resistance improvement by plasma treatment after etching the contact hole NAM-GUN KIM, SUNG-IL CHO, YOON-JAE KIM, CHAN-MIN LEE, JI-HEE KIM, CHEOL-KYU LEE, SEOK-WOO NAM, *Samsung Electronics* PROCESS DEVELOPMENT TEAM As the feature size diminished, it becomes important to control the interconnect resistance, especially, on the interface. Conventionally CF_4 based plasma and HF treatment have been used to remove damaged layer induced during etching the contact holes. However, these methods were limited due to contact enlargement or increment of recess depth. We developed the new treatment to improve contact resistance using H_2/N_2 plasma. The H_2/N_2 plasma assisted treatment (HAT) after etching contact holes improve the cell current 4% compared with the conventional method. Based on the XPS (X-ray Photoelectron Spectroscopy) and OES (Optical Emission Spectroscopy) analysis, it was found that HAT effectively removed the SiC layer. The atomic concentration of carbon on the surface decreases from 22.3% to 1.5% on the XPS analysis by HAT. Though the carbon concentration on the surface significantly decrease during HAT, the contact profile changed less than 5Å, so that the leakage current of gate, called as short channel effect, rarely degraded.

NW1 28 Seeking Methods to Reduce the Aspect Ratio Dependence in Deep Silicon Etch* ROBERT L. BATES, M.J. GOECKNER, L.J. OVERZET, *The University of Texas at Dallas* We are examining how to reduce the Aspect Ratio Dependence (ARD) of deep silicon etch processes while maintaining both smooth sidewalls and an acceptable etch rate. In particular, SF6/O2/Ar and SF6/C4F8/Ar plasmas have both been shown to etch silicon with good anisotropy in a continuous etch process producing good sidewall profiles and at acceptable etch rates. Unfortunately, these processes also suffer from significant ARD. We are proposing to use an ARD deposition process to balance the ARD of the etch process and thereby find a reasonably AR independent process having an acceptable overall etch rate. To do this, we propose to examine both the ARD deposition rate into various AR trenches and the ARD etch rate of the passivation layer in those trenches. We are pursuing this in part because other researchers have shown that the etch rate of low AR features can be reduced (by depositing a passivation layer) and allow larger AR features to "catch up." As a result, the same depth trench can be obtained [1]. The work is being carried out in a Plasma-Therm Versaline reactor in the UTD clean room.

*Special Thanks to K. Kirmse, A. Ali of Texas Instruments Inc. Acknowledgement: This material is based upon work supported in part by the SRC under award number 2012-VJ-2261.

[1]See for example: S. Lai, D. Johnson, and R. Westerman, J.Vac. Sci. Tech. A **24**, 1283 (2006).

NW1 29 Feature Profile Simulations and Finite Penetration Depth PAUL MOROZ, DANIEL MOROZ, *Tokyo Electron US Holdings* In plasma materials processing, energetic ions, neutrals and UV photons typically penetrate deep inside solid materials breaking atomic bonds and displacing atoms on their paths. These important phenomena are rarely taken into consideration in processing simulation software, primarily because the proper penetration depths and the corresponding energy depositions, breaking bonds, and atom displacements are difficult and computationally expensive to compute. The FPS-3D feature profile simulator [1-2] is doing that computationally efficiently by utilizing tabulated results obtained with other methods. We discuss, compare, and present results of such simulations made with different methods, one of which is the molecular dynamics analysis. In general, molecular dynamics could be used for simulating materials processing, etching and deposition, but it is extremely computationally expensive to be used for large groups of atoms. In practice, molecular dynamics methods are too slow to be used for feature profile simulations. However, they could help in defining proper chemical reactions and corresponding rates to be used in an advanced feature profile simulator such as FPS-3D. We present results of FPS-3D simulations for Si and SiO2 etching in Ar/Cl2 and Ar/C4F6/O2 plasmas.

[1]P. Moroz, "General Feature Profile Simulator FPS-3D," ECS Transactions **35**, 25 (2011).
[2]P. Moroz, "Numerical Simulation of Feature Profile Evolution using FPS-3D," IEEE Transactions of Plasma Science **39**, 2804 (2011).

NW1 30 Precise plasma process control based on combinatorial plasma etching MAKOTO SEKINE, TOSHIYA SUZUKI, KEIGO TAKEDA, HIROKI KONDO, KENJI ISHIKAWA, *Nagoya University* YUICHI SETSUHARA, *Osaka University* MASAHARU SHIRATANI, *Kyusyu University* MASARU HORI, *Nagoya University* For the realization of super-fine plasma etching process, fluctuations of plasma parameters such as densities of radicals, ions and electrons is required to be minimized. In particular, conditions of inner surface of reactor wall can significantly influence on the radical density in subsequent plasma process owing to outgas consisting of deposited reaction products and adsorbed species from the previous process on the wall. To investigate variety of gaseous radical densities for H_2/N_2 plasma when inner wall condition was changed by the previous process, we analyzed the radical densities using vacuum ultraviolet absorption spectroscopy (VUVAS). It was clearly confirmed that the radical densities in 100-MHz capacitively coupled plasma (CCP) of H_2/N_2were temporally changed subsequently after different kind of conditions for H_2/N_2 plasma, O_2 plasma, and air exposure. We clarified how and what kind of etched products or process gases adsorbed on inner wall surface during the previous process and what species desorbed from the wall into bulk plasmas. Then we are trying to establish a precise process control systematically based on the plasma nano-science database that is constructing using the combinatorial plasma etching approach [1].

[1]C. Moon *et al.*, Applied Physics Express **2** (2009) 096001.

NW1 31 GPU based 3D feature profile simulation for plasma etch process DEOG-GYUN CHO, *Chonbuk National University* DONG-HUN YU, *Kyung Won Tech.Inc* YEONG-GEUN YOOK, *Chonbuk National University* WON-SEOK CHANG, *National Fusion Research Institute* POO-REUM CHUN, SE-A LEE, YEON-HO IM, *Chonbuk National University* Recently, one of the critical issues in the plasma etching processes of the nanosize devices is to achieve ultra-high deep contact hole without abnormal behaviors such as sidewall bowing and necking However, it is well-known that the predictable modeling for this plasma etching process needs heavy computations due to the inherent complexities of plasma physics and chemistry. As an effort to address this issue, we have developed ultra-fast 3D feature profile simulation codes using CUDA computing technology. In this work, the 3D feature profile simulation is mainly composed of level set based moving algorithm, ballistic transport module and surface reaction module. Especially, the ballistic transport module requiring the time consumable computations are improved drastically by CUDA based numerical schemes, leading to the real time computation. Finally we demonstrated real-time 3D feature profile simulation for ultra-high aspect contact hole etching under fluorocarbon plasma.

NW1 32 Preparation of Alq_3 thin films using a pulsed laser deposition method with cooling target by liquid nitrogen YOSHIAKI SUDA, TAMIKO OHSHIMA, HIROHARU KAWASAKI, TOSHINOBU SHIGEMATSU, YOSHIHITO YAGYU, TAKESHI IHARA, *Sasebo National College of Technology* We have prepared Alq_3 (tris (8-hydroxyquinoline) aluminum) thin films for organic electroluminescence by a pulsed laser deposition (PLD) method. The bulk Alq_3 target was not able to produce by sintering above 1,000 °C, because the glass transition temperature of Alq_3 was about 160 °C. Therefore, the density of Alq_3 target (about 1.3 g/cm^3) was lower than that of the target used by PLD generally. In order to stabilize the density of the Alq_3 target, we cooled the target by liquid nitrogen. The temperature of Alq_3 target cooled by liquid nitrogen was −120 °C. In this study, we have prepared Alq_3 thin films by a Nd:YAG laser (532 nm) deposition method with the cooling target by liquid nitrogen. The experimental results suggest that Alq_3 thin films are deposited at the fluence above 2.3 J/cm^2. FT-IR spectra of the prepared films are as same as those of the Alq_3 powder. UV-Vis spectrum shows that the prepared films have an absorption peak around 400 nm, which is distinct absorption peak of Alq_3. The results suggest that structural and optical properties of the films prepared by cooling target are in agreement with Alq_3 for organic electroluminescence.

NW1 33 Study of thin film formation using an rf non-thermal plasma jet at atmospheric pressure* FLORIAN SIGENEGER, JAN SCHÄFER, RÜDIGER FOEST, DETLEF LOFFHAGEN, KLAUS-DIETER WELTMANN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* The deposition of thin films using an RF-excited plasma jet at atmospheric pressure has been investigated. On flat polymer and glass samples, thin silicon-organic films have been deposited in static experiments using the silicon containing molecules HMDSO and OMCTS. The deposited films have been analysed using profilometry and Fourier transform infrared spectroscopy depending on power and flow rate. High quality films with an O/Si ratio close to two were found for laminar flow regimes. A two-dimensional axisymmetric fluid model describes the interaction of gas heating and flow, the plasma generation in the active volume, the transport of active plasma particles into the effluent and the generation and transport of precursor fragments towards the substrate surface. A remarkable influence of the gas flow on the plasma kinetics is observed only with respect to the density of molecular argon ions, which are transported together with electrons into the effluent. The calculated flux of precursor fragments onto the substrate surface qualitatively agrees with measured profiles of the film thickness.

*The work was supported by the Deutsche Forschungsgemeinschaft within SFB TRR 24.

NW1 34 High Power Pulsed Magnetron Sputtering for Deposition of Amorphous Carbon Films* TAKASHI KIMURA, RYOTARO NISHIMURA, *Nagoya Institute of Technology* High power pulsed magnetron sputtering technology has been recently attracted, because target species sputtered by energetic ion bombardment are highly ionized and the energy of the ions is high enough to modify the substrate surface. In this study, the relationship between the properties of deposited films and the operating conditions of the high power pulsed plasmas has been experimentally investigated. The distance between the carbon target (80mm in diameter) and the substrate is 55mm, and the strength of magnetic field is approximately 0.04T in the vicinity of the target surface. In our experiment, the dissipated power and the repetition frequency are fixed at 50W and 50Hz, respectively. On the other hand, the maximum of instantaneous power is varied from 5kW to 30 kW by changing the duty ratio, and the magnitude of the current is also varied up to 40A. The typical deposition rate is around 5nm per minute and the typical film thickness is around 0.6μm. The films can be regarded as diamond-like carbon (DLC) films. The maximum of the hardness increases with the magnitude of the pulsed current and reaches 18GPa at 35A.

*This work is partially supported by Grant-in-Aid from the Japan Society for the Promotion of Science.

NW1 35 Plasma modification in a rotating reactor of vanadium oxide for electro-chromic devices GAMZE ONGOREN, MUHAMMED SANCAK, *Suleyman Demirel Universitesi* SORIN MANOLACHE, *University of Wisconsin-Madison* NESLIHAN NOHUT, ALI GULEC, AYSEGUL UYGUN, LUTFI OKSUZ, *Suleyman Demirel Universitesi* Titanium as doping material in spraying solution has been reported to enhance properties of electrochromic devices based on vanadium oxide. In this contribution, titanium tetrachloride plasma has been used for treatment of vanadium oxide powder. The treatments have been performed in a glass rotating reactor using ferrofluidic feedthroughs operated at 100 mTorr pressure and 100 W 13.56 MHz RF power; the reaction volume is 1 L and the RF coupling is capacitive using conformal copper electrodes outside of glass cylinder. UV-visible spectroscopy has been used for plasma diagnostic. Plasma treated and untreated vanadium oxide powders have been used for deposition of 100 nm electrochromic layers on ITO conductive electrodes; the deposition has been done by pyrolysis spraying hydrogen peroxide solution of materials. The deposited layers have been characterized by cyclic voltammetry, visible spectroscopy, AFM, SEM and EDS. The devices have been investigated in visible spectral range for optical transmission and color changes with applied voltages. This Work has been supported by TUBITAK TEYDEB project no: 9100036.

NW1 36 Plasma characteristics of PTFE and hexafluoropropene deposition on AISI 1050 Stainless steel for lubrication ERDOGAN TEKE, FERHAT BOZDUMAN, ALI GULEC, HATICE VAROL, SORIN MANOLACHE, *Suleyman Demirel University* ERDEM CAMURLU, *Akdeniz Universitesi* CAHIT KURBANOGLU, LUTFI OKSUZ, *Suleyman Demirel University* Optical and electrical characteristics of sprayed polytetrafluoroethylene (PTFE) by Argon plasma and also hexafluoropropene (C_3F_6) plasma were measured for different plasma parameters (treatment time, type of gas, power, pressure, electrode distance). The coated thin film onto AISI 1050 stainless steel characteristics were also investigated. After the deposition, surface morphology was analysed by Scaning electron microscope (SEM), Energy-dispersive X-ray spectroscopy (EDS), Atomic force microscope (AFM). Abrasion of samples was tested. As a result of abrasion test the PTFE plasma processes more effective than C_3F_6 coating. This Work has been supported by TUBITAK TEYDEB project no: 9100036.

NW1 37 Enhancing antibacterial properties of UHMWPE via ion implantation VINCENZO NASSISI, DOMENICO DELLE SIDE, LUCIANO VELARDI, *Department of Mathematics and Physics - University of Salento* PIETRO ALIFANO, ADELFIA TALÀ, SALVATORE MAURIZIO TREDICI, *Di.S.Te.B.A. - University of Salento* In the last decades, the demand for biomaterials of antimicrobial quality sensibly increased. The essential properties of these materials must be the biocompatibility, wettability, durability and their antibacterial characteristics. One of the most important biomaterial for medical applications is the ultra high molecular weight polyethylene (UHMWPE) that it is used to make components of prosthetic knee, hip and shoulder. It is well known that the presence in UHMWPE of Ag atoms increase its antibacterial properties while Cu and its alloys are known as natural antimicrobial materials. In this work it is proposed a dedicated laser ion source (LIS) accelerator to perform ion implantation together with a systematic study of the surface properties of UHMWPE samples treated with different metals in order to modify their antibacterial characteristics. The proposed technique consists in the application of a dose of specific ions inside the first layer of the sample to be treated. This goal can be effectively achieved if the ions are preventively accelerated. This technique seems to be interesting, since it can open the way to an easier realization of antibacterial materials using various metal ions.

NW1 38 Industrial application of the decomposition of $CO_2 \cdot NO_x$ by large flow atmospheric microwave plasma LAMP employed in motorcar* ANIL PANDEY, SYUNTA NIWA, YOSHINARI MORII, SHUNJIRO IKEZAWA, *Chubu University* In order to decompose $CO_2 \cdot NO_x$ [1], we have developed the large flow atmospheric microwave plasma; LAMP [2]. It is very important to apply it for industrial innovation, so we have studied to apply the LAMP into motorcar. The characteristics of the developed LAMP are that the price is cheap and the decomposition efficiencies of $CO_2 \cdot NO_x$ are high. The mechanism was shown as the vertical configuration between the exhaust gas pipe and the waveguide was suitable [2]. The system was set up in the car body with a battery and an inverter. The battery is common between the engine and the inverter. In the application of motorcar, the flow is large, so the LAMP which has the merits of large flow, high efficient decomposition, and cheap apparatus will be superior.

*The work was partly supported by the funds of Knowledge Cluster and Chubu University.

[1]H. Barankova, L. Bardos, ISSP 2011, Kyoto.
[2]S. Ikezawa, S. Parajulee, S. Sharma, A. Pandey, ISSP 2011, Kyoto (2011) pp. 28–31; S. Ikezawa, S. Niwa, Y. Morii, JJAP meeting 2012, March 16, Waseda U. (2012).

NW1 39 Time constants in the transition between equilibrium and nonequilibrium combustion states of premixed burner flame irradiated by pulsed microwave K. SASAKI, *Hokkaido University* K. SHINOHARA, *Nagoya University* We investigated the time constants in the transition between the equilibrium and nonequilibrium combustion states. We examined the temporal variations of the optical emission intensities from the flame irradiated by pulsed microwave. The transitions (optical emissions) we detected were $C^3\Pi_u - B^3\Pi_g$ of N_2, $A^2\Sigma^+ - X^2\Pi$ of OH, $A^2\Delta - X^2\Pi$ of CH, and continuum at a wavelength of 430 nm. The temporal variations were approximated using exponential functions. The rise and fall time constants of the optical emission intensity of N_2 were 0.35 and less than 0.05 ms, respectively. Both the rise and fall time constants of the optical emission intensities of OH and CH were 0.35-0.4 ms, while the rise and fall time constants of the continuum optical emission intensity were 0.5 ms, which coincided with the time constant of the transport (flow) loss of particles. It is considered that the fall time constant of N_2 represents the heating (cooling) time constant of the electron energy, while its rise time constant represents the loss time constant of electrons. The time constants of electrons, OH, and CH are governed mainly by the transport loss, but the experimental results suggest additional frequencies of $(0.5 - 1) \times 10^3$ Hz for their volume losses.

NW1 40 Laser-induced breakdown stabilization of non-premixed jet diffusion flames MOON SOO BAK, MARK A. CAPPELLI, *Stanford University* Laser-induced breakdown is used to stabilize non-premixed jet diffusion flames under co-flow conditions well exceeding flame blow-off. Our focus has been on methane, ethane, and propane in co-flowing air. The 23 mJ, 10 ns pulse width frequency doubled output from a 15 Hz repetition rate Nd: YAG laser is focused down by a lens to generate the plasma kernel. Gas chromatography is carried out at downstream locations to determine the extent of combustion. The same laser pulse is used to carry out laser-induced breakdown spectroscopy (LIBS) to characterize the fuel-air mixing and to obtain the local equivalence ratios in the flow. Effective stabilization is found for all of the tested fuels but only when the laser-produced plasma is generated in regions of the flow where the local equivalence ratio is around a critical value. With the use of a numerical simulation, we discuss the prospects of using distributed laser pulses for volume plasma filling and control of complex jet flames.

NW1 41 Nanosecond repetitively pulsed discharge control of premixed lean methane-air combustion MOON SOO BAK, MARK A. CAPPELLI, *Stanford University* Two-dimensional kinetic simulations are carried out to investigate the effects of the discharge repetition rate and pulse width of nanosecond repetitively pulsed discharges on stabilizing premixed lean methane-air combustion. The repetition rate and pulse widths are varied from

10 kHz to 50 kHz and from 9 ns to 2 ns respectively, while the total power is held constant. The lower repetition rates, because of their higher pulse energies, produce a larger fraction of radicals such as O, H, and OH. Surprisingly, however, the effect on flame stabilization is found to be essentially the same for all of the tested repetition rates. The shorter pulse width is found to favor the production of species in higher electronic states, but the varying effects on stabilization is also found to be small. Our results indicate that the total deposited power is the critical element that determines the extent of stabilization over this range of discharge properties studied.

NW1 42 Gas-phase Reactive Oxygen and Nitrogen Species in Air Surface Dielectric Barrier Discharges by FTIR and UV spectroscopy HUNG-WEN CHANG, *Department of Chemical Engineering, National Taiwan University* YUKINORI SAKIYAMA, *Department of Chemical and Biomolecular Engineering, University of California, Berkeley* CHENG-CHE HSU, *Department of Chemical Engineering, National Taiwan University* DAVID B. GRAVES, *Department of Chemical and Biomolecular Engineering, University of California, Berkeley* Atmospheric pressure plasmas are considered promising for biomedical treatment purpose due to the production of reactive oxygen species and reactive nitrogen species during the discharge. In this study, a surface microdischarge system which operates at 10 kHz, 0.01 – 1 W/cm^2 in ambient air is used. FTIR and UV-absorbance are used to investigate the time-average gas phase composition and time-resolved ozone concentration, respectively. The results showed that the gas composition is greatly influenced by the power consumption in plasmas. At 0.3 W/cm^2, the gas phase is dominant by NOx species and nearly no ozone is observed while at 0.05 W/cm^2 the amount of NOx is less and the ozone is dominant. Also, time-resolved ozone measurement by means of UV (254 nm) absorbance shows that ozone concentration reaches higher than 1000 ppm in the first tens of seconds and quenched within 1 minutes at high power condition. However, at low power condition no obvious quench of ozone is observed and the ozone concentration attains a steady state in response to the equilibrium of ozone generation and diffusion loss.

NW1 43 Viability and apoptosis of cultured cancer cells induced by atmospheric pressure plasma jet HEA MIN JOH, SUN JA KIM, TAE HUN CHUNG, SUN HEE LEEM, *Dong-A University* Recent studies have shown that atmospheric pressure plasmas are a possible candidate in cancer therapy. In the case of biological structure damage induced by plasma treatment, the primary role is played by reactive oxygen species (ROS), UV photons, charged particles and electric fields. Among them, extracellular and intracellular ROS produced by plasma are considered to be the key constituents that induce cellular changes and apoptosis. These changes were different depending on the discharge conditions controlled by many operating parameters including applied voltage, driving frequency, supply gas and flow rate, and treatment time. Thus, the effects of operating parameters including working gases, plasma dose, treated time and media on cellular changes in plasma-cell interactions need to be investigated. The cellular changes in cultured cancer cells were detected using TUNEL assay with DAPI staining. Cell viability was investigated by using MTT assay which is a method for measurement of metabolic events leading to a reduction in cell survival and necrosis or apoptosis. Also we examined whether cell viability was dependent on plasma-induced cellular ROS generation.

NW1 44 Effect of Neoangiogenesis Using Micro-spot Atmospheric Pressure Plasma CHIHIRO TSUTSUI, *Nano Carbon Bio Device Research Center, Tokyo City University* TOSHIFUMI KOMACHI, TAKUMI KISHIMOTO, *Department of Biomedical Engineering, Tokyo City University* TAKAMICHI HIRATA, AKIRA MORI, *Department of Biomedical Engineering and Nano Carbon Bio Device Research Center, Tokyo City University* Using an in vitro model, we investigated the effect of the atmospheric pressure plasma irradiation to NIH3T3 and porcine aortic endothelial cells. In the plasma exposure experiment using cell proliferation was inhibited in proportion to processing time. However, it was found that this inhibitory effect was suppressed by plasma irradiation and cells are rather on an increase trend. And, in comparison with the cell growth curve for the He gas flow group, the curve for the plasma irradiation group was shifted to the left. We investigated expression analysis in the subsequent experiment with focus on factors related to angiogenesis, it was found that the transient overexpression of VEGF are observed in 24 h from the plasma irradiation. This proliferative effect is likely related to several growth factor releases due to plasma-induced reactive ion/radical interaction.

NW1 45 Development of plasma apparatus for plasma irradiation to living cell model* YOSHIYUKI SUDA, RYO KATO, HIDETO TANOUE, HIROFUMI TAKIKAWA, *Dept. of Electrical and Electronic Information Eng., Toyohashi Univ. of Technol.* RYUGO TERO, *EIIRIS, Toyohashi Univ. of Technol.* Atmospheric pressure plasma has been studied for the industrial applications of biotechnology and medical care. For the development of these fields, understanding the influence of atmospheric pressure plasma on living cell and the mechanism of cell death is necessary. We focus on a basic structure of cell membrane, called lipid bilayer. Lipid bilayer is composed of lipid molecules with an amphipathic property and can be formed on hydrophilic substrates. In this paper, we report the development of the plasma apparatus for the treatment of lipid bilayer. The plasma apparatus uses a typical dielectric barrier discharge (DBD) system and employs parallel plate electrodes with a gap distance of 1 mm [1]. Each electrode is covered with a quartz plate and the substrate temperature is kept constant by cooling medium. The lower quartz electrode has a dimple, in which the substrate coated with a lipid bilayer and buffer fluid are mounted.

*This work has been partly supported by the Research Project of the Venture Business Laboratory from Toyohashi Univ. of Technol. and a Grand-in-Aid for Scientific Research from the Ministry of Education, Culture, Sport, Science and Technology (MEXT).

[1] Y. Sugioka *et al.*, IEEE Trans. Plasma Sci., in press.

NW1 46 Body tissue activation using micro-spot atmospheric pressure plasma source TAKUMI KISHIMOTO, *Department of Biomedical Engineering, Tokyo City University, Tokyo, 158-8557, Japan* TAKAMICHI HIRATA, *Department of Biomedical Engineering, Nano Carbon Bio Device Research Center, Tokyo City University, Tokyo, 158-8557, Japan* CHIHIRO TSUTSUI, *Nano Carbon Bio Device Research Center, Tokyo City University, Tokyo, 158-8557, Japan* MASAHIRO AKIYA, AKIRA MORI, *Department of Biomedical Engineering, Nano Carbon Bio Device Research Center, Tokyo City University, Tokyo, 158-8557, Japan* Experiments have been performed involving directly irradiating body tissues with atmospheric pressure plasma for various medical engineering applications of plasmas. Plasma irradiation was used to burn back dermis of rats. Then, healing and improvement of the scald areas were observed. Additionally, we devoted attention to the angiogenesis, which is a key component of the healing mechanism. Plasma irradiated rats and non treatment were performed an intravenous injection of fluorescein isothiocyanate (FITC) labelled tomato-lectin. The neo-vascular vessels were observed by a confocal laser scanning microscopy, and the quantities were calculated. Each quantity was the non treatment: 9.2 +/– 0.77 and plasma irradiation: 18.4 +/– 2.9. These data indicates that direct plasma irradiation involving ion/radical may promote angiogenesis, and it promotes living-body activation.

NW1 47 Self-consistent collisional-radiative model for shock tube in Jupiter atmosphere* GIANPIERO COLONNA, DANIELA LUCIA PIETANZA, GIULIANO D'AMMANDO, *CNR-IMIP Bari* CNR-IMIP BARI TEAM Modeling vehicle entering in planetary atmospheres is a complex problem involving thermal and chemical non-equilibrium interacting with the radiation field. In this contribution we present a kinetic model that couples self-consistently the free electron Boltzmann equation, state-to-state chemical kinetics and radiation transport equation for shock wave in Jupiter atmosphere. The rapid growth of the translational temperature, induce the increase of the energy of internal degrees, followed by dissociation and ionization. The radiation causes non-local effects, because the radiation emitted inside the shock wave, can be absorbed in different location. The fluid dynamic equations considered here are those of the one-dimensional stationary shock tube. Collisional-radiative model of hydrogen and helium atoms has been considered, including atom-atom collisions. Non-equilibrium distributions arise, showing steps and plateaux, inducing anomalous behaviors as non-monotone trend of the internal temperature of atomic species and strong interaction between the radiation field and the ionization degree.

*Funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 242311.

NW1 48 Effect of the voltage waveform on induced flow of a dielectric barrier discharge plasma actuator NAOHIKO SHIMURA, MOTOFUMI TANAKA, HIROYUKI YASUI, *Power and Industrial Systems R&D Center, Toshiba Corporation* Flow control technique using surface plasma is attracting a lot of attention because of its ability to be the innovative technology for the wide range application. In this paper, we have conducted experiments to inspect relationship of velocity of the induced flow, frequency and voltage of power source. First, when sinusoidal voltage was applied between the electrodes, the result showed the induced flow was the faster, the greater the power was, regardless of the frequency and voltage. Then, the waveform was changed to bipolar pulse with shorter ON period than that of sine wave with a frequency of 3 kHz, almost the same induced velocity was observed at the same power, regardless of the voltage waveform. By the same experiment with a frequency of 10 kHz, the relationship of induced velocity and the power was affected by the waveform unlike the case of frequency at 3 kHz. The highest induced velocity was observed in case of sine wave. Induced velocity was able to be expressed as a function of the full width half maximum of voltage waveform, under constant power. From these facts, it is believed that it is required for external electric field to be applied for more than certain period of time in order for ions to be accelerated by electric field even in a case that almost same amount of ions were generated under an almost same condition of discharge power.

NW1 49 Plasma aerodynamic control of both subsonic and supersonic flows SEONG-KYUN IM, MARK A. CAPPELLI, *Stanford University* We present both subsonic and supersonic aerodynamic flow control studies using dielectric barrier discharge (DBD) actuators. Flow-aligned DBD actuators designed to impart spanwise forcing and create streamwise vorticity are used for reattaching separated subsonic flows on inclined flat plates and trailing angled flaps. We demonstrate enhanced control authority when these DBD actuators are used in conjunction with boundary layer bleeding, also driven by DBD actuators within the bleed channels. DBD actuators of similar configuration are also used to control boundary layer separation in unstarting supersonic flows at Mach 4.7 flow condition. In these unstart studies, planer laser Rayleigh scattering is used to visualize flow features such as boundary layer thinning, thickening, and shock waves. A significant thinning of the boundary layer is observed with DBD actuation and spanwise forcing. This thinning is the result of the drawing in of high speed fluid from the supersonic core and is shown to lead to a delay in the unstart process.

NW1 50 Plasma assisted combustion of paraffin mixture OLEG NEDYBALIUK, VALERIY CHERNYAK, EUGENE MARTYSH, OLENA AKTAN, *Taras Shevchenko National University of Kyiv* SVITLANA ORLOVSKA, *Odessa National Universiy* NATALIA BELENOK, *National Technical University of Ukraine "Kyiv Polytechnic Institute"* TAMARA LISITCHENKO, *Taras Shevchenko National University of Kyiv* The question of the additional activation of paraffin based solid fuels is examined. The use of plasma stimulation for this purpose is proposed. The mixture of n-paraffin and stearin in the solid state as the model of the solid paraffin based fuel is used. The plasma assisted combustion of this model is experimentally investigated. The voltage-current characteristics of discharge at the different regimes are measured. The emission spectrums of a flame and the plasma torch emission spectrum are obtained. The population temperatures of excited rotational levels and the flame temperature are determined.

NW1 51 Laser Induced Fluorescence Measurements of Ion Velocity in Magnetic Cusped Plasma Accelerators* NATALIA MACDONALD, MARK CAPPELLI, *Stanford University* WILLIAM HARGUS, JR, *Air Force Research Laboratory, Edwards AFB* Cusped Field Thrusters (CFTs) are magnetized plasma accelerators that use strong cusps to shape the magnetic field and hence the electrostatic potential. The cusped magnetic field lines meter the electron transport to the anode and reduce the energetic ion flux towards the dielectric channel walls, thereby reducing the effects of erosion. This work presents time averaged laser induced fluorescence velocity measurements of the ions in the plumes of three CFT variants. These include the Cylindrical Hall Thruster (CHT), Cylindrical Cusped Field Thruster (CCFT), and Diverging Cusped Field Thruster (DCFT). Results indicate that magnetic cusps form equipotential surfaces, and that the majority of ion acceleration occurs outside of the thruster channels.

*Research is funded through the Air Force Office of Scientific Research with Dr. M. Birkan as grant monitor.

NW1 52 Influence Of Secondary Electrons Produced From Plasma Material Interaction In Presence Of Crossed Electric And Magnetic Fields* KAPIL SAWLANI, JOHN FOSTER, *University of Michigan* The electron energy distribution function (EEDF) plays a very important role in determining thruster efficiency as it determines various gas phase reaction rates. In Hall thrusters, secondary electron emission derived from the interaction of energetic electrons with ceramic channel surfaces influence the overall shape of the EEDF as well as determine the potential difference between the plasma and wall. The role of secondary electrons on the discharge operation of Hall thrusters is poorly understood. Experimentally, determining this effect is even more taxing as the secondary electron yield (SEY) varies drastically based on many parameters such as incident electron energies, flux and impact angle, and also on the surface properties such as temperature and roughness. The electron transport is also affected by the profile of the magnetic field, which is not uniform across the length of the accelerating channel. The goal of this work is to map out the variation of the EEDF and potential profile in response to the controlled introduction of secondary electrons. This data is expected to serve as a tool to validate and improve existing numerical models by providing boundary conditions and SEY for various situations that are encountered in Hall thrusters.

*Work supported by Air Force Office of Scientific Research (AFOSR).

NW1 53 WO3 nanoparticles modification for electrochromic applications using a plasma rotating reactor MUHAMMED SANCAK, GAMZE ONGOREN, *Suleyman Demirel Universitesi* SORIN MANOLACHE, *University of Wisconsin-Madison* NESLIHAN NOHUT, ALI GULEC, AYSEGUL UYGUN, LUTFI OKSUZ, *Suleyman Demirel Universitesi* Functional nanoparticles are required for various applications including biotechnology, analytics, nanocomposites, etc. In this contribution, a rotating reactor has been used for treatment of tungsten oxide nanopowder under titanium tetrachloride plasma environments. The reactor volume is 1 L and consist of a Pyrex glass tube. Copper electrodes outside of glass cylinder are used for RF capacitive coupling. Ferrofluidic feedthroughs at both ends of reaction chamber are sealing in order to operate under vacuum conditions. The treatments have been performed at 100 mTorr pressure and 100 W 13.56 MHz RF power. Plasma treated and untreated tungsten oxide powders have been used for deposition by pyrolysis spraying of 100 nm layers from hydrogen peroxide solution on ITO conductive electrodes. The deposited layers have been characterized by cyclic voltammetry, visible spectroscopy, AFM, SEM and EDS. The devices have been investigated in visible spectral range for optical transmission and changes with applied voltages. This Work has been supported by TUBITAK TEYDEB project no: 9100036.

NW1 54 The production of magnetic nanoparticles of Iron Oxide by arc discharge in water HAMID REZA YOUSEFI, SARA FATHOLLAH, MARYAM NIKEYN, SHOHREH KHATAMI, *Plasma Physics Research Center, Science and ResearchBranch, Islamic Azad University, Tehran, Iran* Nanoparticles can be utilized for any practical application. In recent years; considerable attention has been paid to iron oxide magnetic. Iron oxide nanoparticles are the class of nanoparticle which can have useful magnetic properties. In this research, magnetic iron oxide nanoparticles were produced by Arc discharge method in water. Structural analysis carried out by X-ray diffraction analysis (XRD), Scanning Electron Microscopy (SEM), and Spectrophotometer. Various magnetic nanoparticles like iron carbide (Fe3c), magnetic iron oxide (magnetite /maghemite) are obtained by arc discharge method in water. In this work have been showed, the influence of the time duration on the number of magnetic nanoparticles and the influence of the gap between the two electrodes on particle structure and size distribution. Furthermore, when iron nanoparticles are used under applied magnetic field, the particles would move in the direction of magnetic field. When the magnetic field is removed, the particles stop moving and still remain stably suspend in the dielectric liquid.

NW1 55 Study on synthesis processes and crystallinity changes of nanographene materials synthesized by alcohol liquid-plasma HIROKI KONDO, TATSUYA HAGINO, KEIGO TAKEDA, KENJI ISHIKAWA, *Nagoya University* HIROYUKI KANO, *NU-ECO Engineering co. ltd.* MAKOTO SEKINE, MASARU HORI, *Nagoya University* NAGOYA UNIVERSITY COLLABORATION, NU-ECO ENGINEERING CO. LTD. COLLABORATION Nanometer-sized graphene is one of promising materials for novel applications such as electrical device, compound materials, and so forth, owing to its excellent and unique electrical, physical and morphological properties. In recent years, we have realized the high-speed synthesis, over 1mg/min., of the nanographene with high-crystallinity using in-liquid plasma. In this study, elementary steps of nanographene synthesis and crystallinity change during synthesis were investigated. A high-voltage (10 kV) 60 Hz ac-voltage was applied to the two electrodes above and below alcohol surface. After the plasma discharge for 15 minutes, nanographene materials were dispersed in the alcohols and collected by a filtration method. According to the Raman spectra, when ethanol was used, types of metal electrodes did not affect synthesis rates and crystallinity. However, when 1-butanol was used, crystallinity of nanographenes drastically changed depending on types of metal electrodes. It is because different synthesis processes depending on types of alcohols have different dependence on metal electrodes.

NW1 56 PLASMA SCIENCE I

NW1 57 Effects of Boundaries on Plasma Jet Formation* MEHMET AKMAN, *Old Dominion University* ERDINC KARAKAS, *University of Houston* MOUNIR LAROUSSI, *Old Dominion University* The dynamics of non thermal plasma jets consisting of plasma bullets change with background gas pressure. Our recent study indicates that this dependence is not limited to the pressure alone but also to a physical boundary confining the working gas flow. It is observed that in a Helium filled chamber, no plasma bullet propagation occurs; however inside the tube in which the Helium is flown into the chamber, plasma bullet propagation is visible. The physical boundary created by this tube enables the bullets to propagate while the lack thereof inside the chamber results in the diffuse plasma at the same pressure. This boundary does not need to be an object that surrounds the gas flow. This is evident when a background gas different than helium is introduced into the chamber. In this case, at the same pressure (75 torr), the diffuse plasma transitions into a jet as a result of the formation of a helium channel in which the plasma bullets propagate. The background gas creates a boundary layer around the helium flow inside the chamber. Therefore, it is believed that in order for plasma bullets to propagate, there needs to be a boundary surrounding the gas channel. In addition to this visual observation, in the case of helium, emission profile in VIS range also shows distinct transitions, specifically at 587.4nm. In this paper, experimental evidence supporting these observations explained above will be presented.

*Work was funded by an AFOSR grant.

NW1 58 Modeling of radical productions and subsequent decay processes in an atmospheric pressure streamer discharge ATSUSHI KOMURO, RYO ONO, TETSUJI ODA, *The University of Tokyo* A streamer discharge has been considered to be an effective production source of chemically active radicals. However, theoretical understanding of the discharge phenomenon and the chemical kinetics is still poor. This study is devoted to reveal the radical behaviors in an atmospheric pressure streamer discharge in $H_2O/O_2/N_2$ gas mixtures. The present model includes a discharge model, a gas dynamics model and chemical kinetics model with vibrationally excited molecules. It is shown that the numerically obtained axial distributions of O, N and OH radical are consistent with our experimental results. Direct dissociation processes, two-step dissociation with vibrationally excited molecules and a quenching of excited O atoms are predominant for O, N and OH radical productions, respectively. In addition, a gas temperature and decay rates of radicals in post-discharge periods are also compared with our experimental results. Numerically simulated gas temperatures in post-discharge phase increase as humidity increase. This tendency has already shown in our previous experimental results and it is successfully reproduced in our model. It is also shown that the rise in gas temperature affects subsequent radical decay processes.

NW1 59 Effect of rare gas and product concentration on the electron kinetics of He/CH4/CO2 mixtures for Syngas production* VASCO GUERRA, *Instituto de Plasmas e Fusao Nuclear, Instituto Superior Tecnico, Universidade Tecnica de Lisboa, Portugal* ANDRÉ JANECO, NUNO PINHÃO, *Instituto Tecnologico e Nuclear, Instituto Superior Tecnico, Universidade Tecnica de Lisboa, Portugal* In this work we study the electron kinetics in $He/CH_4/CO_2$ mixtures with the objective of studying Syngas production in cold or warm plasmas. The electron Boltzmann equation is solved in a hydrodynamic regime in a density gradients expansion, using a discrete ordinates numerical method. The electron collision cross sections used are based on sets published by different authors, mostly tested on two-term angular expansion solvers. However the cross sections were modified to ensure coherence between the transport parameters obtained with our Boltzmann solver and the experimental transport parameters. Warm plasma conditions are studied including both super-elastic collisions and multistep electronic excitation and ionization from vibrational excited levels, mechanisms usually neglected in electron kinetic studies in CH_4 and CO_2. The influence of the rare gas concentration, vibrational temperature and product (CO and H_2) concentrations on the electron velocity distribution function, transport parameters, collision frequencies and fractional power losses is discussed. These results allow the identification of the main energy transfer channels and are a necessary step for the develop a full kinetic model.

*AJ thanks the FCT grant SFRH/BD/63234/2009. VG thanks the FCT funding to IPFN-LA.

NW1 60 Experimental characterization of the electron transport across a magnetic field barrier F. GABORIAU, R. BAUDE, L. LIARD, G.J.M. HAGELAAR, *CNRS, Universite de Toulouse* Magnetized plasma transport plays a key role not only in fusion plasmas but also in low-temperature plasma sources operating at low pressure. Due to the presence of chamber walls, magnetized low-temperature plasmas can show ill-understood complex behavior while most available experimental data is too application-oriented and not detailed enough for model validation. In this context, the objective of that work is to study the magnetized transport as a problem of its own. A new dedicated laboratory set-up with flexible magnetic field has been built with simple but detailed diagnostics of the plasma transport. In addition to the commonly used Langmuir probe diagnostic, we have developed space-resolved wall-current measurements to characterize the different transport regimes governed by the classical cross field mobility and magnetic drifts. We will present and discuss the first experimental results obtained in argon discharges by varying the magnetic field intensity and the DC bias voltage on an electrode placed in front of the magnetic field region. This work is supported by French National Research Agency (project METRIS ANR-11-JS09-008).

NW1 61 Bi-ionic Dust Solitary Waves* JULIO PUERTA, PABLO MARTIN, *Universidad Simon Bolivar* Propagation of nonlinear solitary waves in dusty plasmas with two ions is analyzed. In the present treatment the mass of one of ions is assumed to be much smaller than the other one, in such way that there is enough time for ions to reach quasi thermal equilibrium. Maxwell Boltzmann factors are therefore applied for the ions an the whole dynamic is on the grain. Now we use the method of the pseudo-potential taking in to account temperature effects in function of the density of the heavy ion. In the limit where the heavy ion density tends to zero we recover effects found by other authors. Several numerical calculations for different values of the characteristic parameters will be shown using dimensionless variables.

*Work supported by grant DID-G22, Universidad Simon Bolivar, Caracas - Venezuela.

NW1 62 Determination of collisional quenching rate coefficient of $N_2(A^3\Sigma_u^+)$* YUUSUKE KOIZUMI, SUSUMU SUZUKI, HARUO ITOH, *Chiba Institute of Technology* We have previously determined the collisional quenching rate coefficient of $N_2(A^3\Sigma_u^+)$ by an air pollutant gas [1-4]. In this paper we report the collisional quenching rate coefficient k' of $N_2(A^3\Sigma_u^+)$ by p-xylene (C_8H_{10}), which was determined to be $(6.5\pm0.9)\times10^{-9}$ cm^3/s. In addition, through repeated experiments it was found that by-products of p-xylene were deposited on the cathode, similarly to the cases of m-xylene and o-xylene previously reported [4], and then the current-voltage curves consistently shifed to a higher-E/p_0 region. To clarify the reason for this behavior, we confirmed by Auger electron spectroscopy (AES) and Fourier transform infrared spectroscopy (FTIR) that these changes in the current-voltage curves were caused by the deposition of a thin film of by-product of decomposed xylene on the cathode surface. According to the results of AES, C atoms were detected in a sample exposed to an electrical discharge, and we confirmed that the deposit of C was thickest in the case of electrical discharge in p-xylene. According to the results of FTIR, it was found that CH_2 and CH were obtained from the deposition of p-xylene.

*This work was supported by JSPS KAKENHI Grant Number 24560344.

[1]S. Suzuki, H. Itoh, H. Sekizawa, and N. Ikuta, J. Phys. Soc. Jpn. **62**, No. 8, 2692–2697 (1993).

[2]S. Suzuki, H. Itoh, H. Sekizawa, and N. Ikuta, Jpn. J. Appl. Phys. **36**, 4744–4746 (1997).

[3]S. Suzuki, T. Suzuki, and H. Itoh, Cont. of HAKONE X Saga, Japan, 132–135 (2006).

[4]S. Suzuki and H. Itoh, Proc. of 30th ICPIG (Belfast, UK), A1–12 (2011).

NW1 63 Nonlocal control of electron temperature in short-discharge plasma with active boundaries* V.I. DEMIDOV, *WVU* S.F. ADAMS, *AFRL* E. BOGDANOV, *SPbSU* M.E. KOEPKE, *WVU* A.A. KUDRYAVTSEV, *SPbSU* It is known that boundaries are very important in formation of nonlocal plasma properties [1]. This study combines experimental and modeling demonstration of controlling electron temperature in a plasma with active boundaries. To demonstrate that, a short dc discharge with cold cathode and application of different voltages to the conducting discharge wall for argon plasma at 1 Torr pressure has been used in experiments and modeling. It is demonstrated in the model for this discharge that spatial distributions of electron density and temperature and argon metastable atom density depend on the dc voltage applied to different conducting parts of the wall. Applied voltage can trap within the device volume energetic electrons arising from atomic and molecular processes in the plasma. This leads to a modification in the heating of slow electrons by energetic electrons and as a result modifies the electron temperature. Conducted experiments also demonstrate that the measured electron temperature is a function of potential applied to the wall and it is possible to see increasing the electron temperature with increasing absolute value of the applied negative potential.

*This work was supported by the DOE OFES (Contract No. DE-SC0001939), GK 14.740.11.0893 and AFOSR.

[1]E. Bogdanov, S. Adams, V. Demidov, A. Kudryavtsev, and J. M. Williamson, Phys. Plasmas **17**, 103502 (2010).

NW1 64 Control of Electron Energy Distribution Functions Using a Tandem Source Reactor* SHYAM SRIDHAR, LEI LIU, WEIYE ZHU, HYUNGJOO SHIN, VINCENT DONNELLY, DEMETRE ECONOMOU, *Department of Chemical and Biomolecular Engineering, University of Houston* The electron energy distribution function (EEDF) governs most of the reactions in plasma processing, as well as determining the intensity and wavelengths of light produced by the plasma. Therefore, measuring and controlling EEDF is essential to understand and develop advanced plasma processing technologies, and suppress damaging vacuum ultraviolet production. With the goal of gaining some added control of the EEDF, we have begun studies of a tandem source plasma reactor consisting of a helical resonator (HR) operating in conjunction with an inductively coupled plasma (ICP) main source. Operating the reactor in this configuration enables us to inject plasma from the dense upstream HR through a metal grid to the downstream ICP. Preliminary studies were conducted using this setup and the effect of upstream plasma on downstream plasma was measured using a Langmuir probe. EEDFs were obtained as a function of gas pressure, bias applied to the boundary electrode, and different grid opening sizes. For grids with openings larger than the sheath thickness, the coupling between the plasmas was found to be strong, compared to grids with openings comparable to the sheath width. In the latter case, the coupling was found to be weaker and population of low energy electrons decreased due to the injection of upstream plasma.

*Work supported by the Department of Energy.

NW1 65 Experimental Studies of Laser-Induced Fluorescence of Kr^{+}* GREG SEVERN, TIM WELSH, *Dept. of Physics, University of San Diego, San Diego, CA, 92110* NOAH HERSHKOWITZ, *Dept. Engineering Physics, University of Wisconsin, Madison, Madison WI 53706* We have succeeded in obtaining a laser-induced fluorescence (LIF) signal from Kr^+ in a low temperature Kr plasma discharge, using a diode laser, for a wavelength near 729nm. An atomic energy level scheme that is accessible to diode lasers is $^4D_{7/2} \rightarrow {}^4P^0_{5/2} \rightarrow {}^4P_{5/2}$. The metastable state, $^4D_{7/2}$, one of several possible metastables states for excitation, proved to be sufficiently populated in the in a low temperature DC plasma discharge ($T_e \sim 1eV$, $T_i \sim 1/40eV$, $n_i \sim 10^9 cm^{-3}$) to produced a high quality signal. The excitation wavelength is nominally 729 nm, and the detected photon is nominally 473 nm. We used an extended cavity diode laser in the Littrow configuration (Sacher-Lasertechnik TEC-100-0730-20). Successful completion of these experiments will provide a new ion velocity diagnostic for Kr ions which will aid in at least 3 basic plasma science experiments: 1) Hall Thruster ion plume measurements, 2) sheath formation in the case of multiple ion species plasmas (with 3 ion species), and 3) studies of the comparison between ion velocities of metastable state rare gas ions and known ground state ion mobilities.

*Work supported by NSF grant nos. CBET-0903832 and CBET-0903783, DOE grant nos. DE-FG02-97ER54437, DE-FG02-03ER54728, DE-FG02- 06ER54845, DE-AC52-07NA27344, DE-FG02-05ER54809, and DE-FG02-07ER54917.

NW1 66 On the application of a physically based higher order fluid model for low-temperature plasmas* NATHAN GARLAND, RON WHITE, ROBERT ROBSON, *ARC Centre for Antimatter-Matter Studies, James Cook University, Townsville, Australia* PETER NICOLETOPOULOS, *Faculté des Sciences, Université Libre de Bruxelles, 1050 Brussels, Belgium* SASA DUJKO, *Institute of Physics, Pregrevica 118, 11080 Belgrade, Serbia* We present a high resolution, computationally efficient non-local fluid model of a low-temperature parallel plate plasma discharge. The non-local model uses low-order velocity moments of the Boltzmann equation representing particle, momentum and energy balance equations, coupled with Poisson's equations to determine space-charge fields. The system of equations is closed used a physically sound heat flux ansatz [1]. A new scheme is implemented for prescribing the relevant collisional terms in the balance equations, based on available electron swarm transport coefficients [2]. The model is applied to simulation of various configurations including the Gaseous Electronics Conference (GEC) reference cell and compared to previous models of the system. Results of the model yield spatial and temporal profiles of electron densities, flux and energy in addition to electric field distributions inside the GEC reference cell. In this paper, we highlight differences associated with local and non-local fluid equation treatments, as well as highlight the importance of correct implementation of electron swarm transport data.

*Support: Australian Research Council

[1]R. E. Robson, R. D. White, and Z. Lj. Petrovic, Rev. Mod. Phys. **77**, 1303 (2005).

[2]R. E. Robson, P. Nicoletopoulos, M. Hildebrandt, and R. D. White, J. Chem. Phys. (submitted).

NW1 67 Investigation of the temporal sheath dynamics in the intermediate RF regime* M. SHIHAB, A.T. ELGENDY, D. EREMIN, T. MUSSENBROCK, R.P. BRINKMANN, *Inst. for Theoretical Electrical Engineering, Ruhr University Bochum* I. KOROLOV, A. DERZSI, Z. DONKO, *Inst. for Solid State Physics and Optics, Wigner Research Centre for Physics, H.A.S.* J. SCHULZE, *Inst. for Plasma and Atomic Physics, Ruhr-University Bochum* The nonlinear dynamics of modulated RF plasma boundary sheaths is investigated employing a recently published model termed

Ensemble In Spacetime (EST) and Particle In Cell (PIC) model. The EST enables a fast, and kinetically self-consistent simulation of all RF modulated plasma boundary sheaths in all technically relevant discharge regimes, (Shihab *et al.*, J. Phys. D: Appl. Phys. **45**, 185202, 2012). A numerical experiment has been done using PIC approach with an electrically and geometrically symmetric capacitively coupled plasma. Using the resulting ion flux to the sheath and the sheath potential as input parameters, the sheath dynamics is simulated with EST as well. The results of EST are in excellent agreement with the PIC results. A huge reduction in the simulation time is achieved using EST. The ion dynamics in the intermediate regime (i.e., the ion transit time is of the order of the RF period) causes a temporal asymmetry for the sheath dynamics. The memory effects due to the ion inertia is supposed to give rise to a phase difference between the expansion and the contraction phases of the plasma sheath and consequently to a hysteresis of the sheath charge voltage relation.

*The financial support from the Federal Ministry of Education and Research within the framework of the project "Plasma-Technology-Grid" and SFB-TR87 is gratefully acknowledged.

NW1 68 Online platform for simulations of ion energy distribution functions behind a plasma boundary sheath* ALEXANDER WOLLNY, MOHAMMED SHIHAB, RALF PETER BRINKMANN, *Ruhr University Bochum* INSTITUTE FOR THEORETICAL ELECTRICAL ENGINEERING TEAM Plasma processes, particularly plasma etching and plasma deposition are crucial for a large variety of industrial manufacturing purposes. For these processes the knowledge of the ion energy distribution function plays a key role. Measurements of the ion energy and ion angular distribution functions (IEDF, IADF) are at least challenging and often impossible in industrial processes. An alternative to measurements of the IEDF are simulations. With this contribution we present a self-consistent model available online for everyone. The simulation of ion energy and ion angular distribution functions involves the well known plasma boundary sheath model by Brinkmann [1–4], which is controlled via a web interface (http://sheath.tet.rub.de). After a successful simulation run all results are evaluable within the browser and ready for download for further analysis.

*This work was supported by the German Federal Ministry of Education and Research via the PT-Gris project and the Ruhr University Research School.

[1] R. P. Brinkmann, J. Phys. D: Appl. Phys. **44**, 042002 (2011).
[2] R. P. Brinkmann, J. Phys. D: Appl. Phys. **42**, 194009 (2009).
[3] R. P. Brinkmann, J. App. Phys. **102**, 093303 (2007).
[4] M. Kratzer *et al.*, J. Appl. Phys. **90**, 2169 (2001).

NW1 69 The Bohm Criterion in Collisional Plasmas: Can the Contoversy be solved?* RALF PETER BRINKMANN, *Ruhr University Bochum* The existence or non-existence of a collisionally modified Bohm criterion is the subject of intense discussion, with contributions by Godyak (Phys. Lett. A 89, 80, 1982), Riemann (J. Phys. D: Appl. Phys. 24, 493, 1991), Valentini (Phys. Plasmas **3**, 1459, 1996), Chen (Phys. Plasmas **5**, 804, 1997), Sternberg (Phys. Plasmas **9**, 4427, 2002), Franklin (J. Phys. D: Appl. Phys. **36**, 2821, 2003), Benilov (IEEE TPS **28**, 2207, 2000), Brinkmann (J. Phys. D: Appl. Phys. **44**, 042002, 2011), and others. All authors agree on the fact that that collisional plasmas do not obey a Bohm criterion in a strict sense, but are add odds whether (and how) such a criterion may be formulated in an approximate sense. This contribution will propose a solution to that controversy. In particular, it will show that Godyak's and Sternberg's thesis on the existence of a collisionally modified Bohm criterion (in the interpretation by Brinkmann) and Riemann's proof of its non-existence are mathematically not in contradiction: they just reflect different opinions on what constitutes a physically reasonable approximation.

*The author gratefully acknowledges financial support by the Deutsche Forschungsgemeinschaft in the frame of Research Group 1123 Physics of Microplasmas.

NW1 70 Plasma-Wall Interaction in Presence of Intense Electron Emission from Walls IGOR D. KAGANOVICH, YEVGENY RAITSES, ALEX V. KHRABROV, MICHAEL D. CAMPANELL, ERINC TOKLUOGLU, HONGYUE WANG, *Princeton Plasma Physics Laboratory* DMYTRO SYDORENKO, *University of Alberta* The plasma-surface interaction in presence of strong thermionic or secondary electron emission has been studied theoretically and experimentally both as a basic phenomenon and in relation to numerous plasma applications. The electron flux to the wall is determined by the electron velocity distribution function (EVDF) and by the sheath potential, which is set by ambipolar condition consistent with the EVDF and the wall emitting properties. Nonlinear coupling between EVDF and sheath potential is responsible for a number of unusual phenomena [1]. We observed new regime where all plasma electrons leave and are substituted by secondary electrons. In this regime, there is practically no electric field in plasma and sheath, so that ions are not drawn to the wall, plasma electrons are not confined and the plasma potential is negative [2]. Finally, methods to control plasma profiles with an auxiliary electrode in dc discharges are studied experimentally [3].

[1] M. D. Campanell *et al.*, Phys. Rev. Lett. **108**, 235001 (2012).
[2] M. D. Campanell, A. Khrabrov, and I. Kaganovich, to be published in Phys. Rev. Lett. **108** (2012).
[3] Y. Raitses *et al.*, IEEE Trans. on Plasma Scie. **39**, 995 (2011).

NW1 71 Fourier Transform Infrared Spectroscopy of Trifluoroiodomethane ICP Discharge* CASSIUS FAGIOLI, DAVID URRABAZO, MATTHEW GOECKNER, *University Of Texas at Dallas* Trifluoroiodomethane (CF3I) is an experimental gas that currently is being considered for semiconductor etching. We will report the breakdown characteristics of CF3I in an ICP plasma. In this study, the gas chemistry was examined through the use of Fourier transform infrared (FTIR) spectroscopy. This allowed us to identify the fraction of CF3I remaining in the discharge as well as some of the daughter species produced. Our results indicate that the major multi-atomic species found in the system include Tetrafluoromethane (CF4) and Trifluoromethyl (CF3). Mass balance examination also suggests the creation of atomic and molecular Iodide.

*Applied Materials.

NW1 72 In-situ Monitoring of Surface Modification of GaN Films Exposed to Inductively-Coupled Plasmas* KEIJI NAKAMURA, MIAO-GEN CHEN, YOSHITAKA NAKANO, HIDEO SUGAI, *Chubu University* This paper reports in-situ monitoring of surface modification of plasma-treated GaN films based on photoluminescence (PL) technique. Irradiation of 313 nm ultraviolet (UV) light induced the photoluminescence of the GaN film, which typically consists of 365 nm luminescence caused by transition between near band edges (NBE) andbroad yellow luminescence (YL) for an approximate wavelength range of 480-700 nm corresponding to defect-states-related transition before plasma exposure. However, after turning on discharges, a broad blue luminescence (BL) of 400-480 nm was also observed, and the BL intensity significantly increased, whereas the NBE and the YL decreased after the plasma exposure. The plasma-induced significant nitrogen deficiency near top surface will cause the decreases in both the NBE and the YL as non-emissive defects, and diffusion of the defects in the depth direction will attribute to the appearance of the BL. These results suggested that the PL measurements is useful for in-situ surface monitoring of plasma-treated GaN films. This work is partly supported by the 2nd stage Knowledge Cluster Initiative and Grant-in-Aid for Scientific Research (C) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

*This work is partly supported by the 2nd stage Knowledge Cluster Initiative and Grant-in-Aid for Scientific Research (C) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

NW1 73 Active Control of the Secondary Electron Emission Coefficient: A New Plasma Control Paradigm?* DAVID URRABAZO, C. LIU, L. OVERZET, *The University of Texas at Dallas* L. RAJA, D. BREDEN, H. HARISWARAN, P.K. PANEERCHELVAM, *The University of Texas at Austin* Many discharges, from low to high pressure, are strongly dependent upon Secondary Electron Emission (SEE) at a cathode surface. As a result, the SEE process is generally thought to play a key role in determining plasma properties. Great efforts have been expended to control SEE from surfaces by controlling the electron work function energy through surface chemistry; but in the end, all of the standard devices suffer from one large detriment: Once the emitter/cathode is built, the magnitude of the SEE Coefficient is set. Control over SEE is possible only through changing the temperature of the surface. Recently published data, however, points to the possibility of controlling the SEE Coefficient of some surfaces in real time through the use of surface embedded electronic devices. We are just beginning an investigation of exactly this. To the best of our knowledge, no such study has ever been attempted even though it could lead to the formation of whole new classes of plasma based devices and systems. In this poster, we will describe the background physics/chemistry of the problem, the beginning of our modeling and experiments as well as the data we have obtained so far.

*This research was supported in part by the US Dept. of Energy.

NW1 74 Large Volume Plasma Production in SRF Cavities with Complex Geometrical Shape JANARDAN UPADHYAY, JOSEPH NEWTON, ALEX GODUNOV, SVETOZAR POPOVIC, LEPSHA VUSKOVIC, *Old Dominion University* Plasma based surface modification is the only technology with promises of in situ processing of superconducting radio frequency (SRF) cavities. These are the electrodynamically resonant components of complex shape, such as accelerating, deflecting, or "crabbing" cavities. Each shape is optimized for the electromagnetic field distribution that is needed to achieve a particularly required performance. As a result, cavity geometry is quite complex at a relatively large volume that is 5–10 liters, approximately. Hence, to create uniform plasma with varying pressure range at the resonant frequency is a nontrivial task. In this work, a simplified model of resonant microwave breakdown and the sustained plasma is developed with the goal to maximize plasma uniformity over the cavity structure. Its results are compared with the experimental results for a 1.5 GHz multiple cell accelerating structure. The model is based on the macroscopic plasma approach and the results were evaluated for the room temperature, non-superconducting conditions. We will discuss conditions and consequences of two cases, where free and ambipolar diffusion are dominant. Besides the symmetrical accelerating structures, the model for more complex, asymmetric, cavities is being developed and will be discussed.

NW1 75 Adsorption and reactivity of O and N atoms on oxide surfaces under plasma exposure D. MARINOV, O. GUAITELLA, A. ROUSSEAU, *LPP, Ecole Polytechnique, UPMC, Universite Paris Sud* Interaction of nitrogen and oxygen atoms with oxide surfaces (SiO2, pyrex, TiO2) was studied. Stable N (O) were grafted to the surface by a low pressure ($\sim$1 mbar) rf discharge in N_2 (O_2) and then characterized by a number of techniques. Conversion and production of new molecules (such as NO, NO_2) on the surface catalyzed by O_{ads} and N_{ads} was investigated using in-situ laser absorption measurements. Reactivity of adsorbed atoms under plasma exposure was studied with isotopic substitution technique. Typically, the pretreated surface containing $^{14}N_{ads}$ (or $^{16}O_{ads}$) was exposed to a pulsed discharge in isotopic gas $^{30}N_2$ (or $^{36}O_2$) and production of $^{14}N^{15}N$ (or $^{16}O^{18}O$) on the surface was monitored using a quadrupole mass spectrometer. This allowed absolute measurements of the density of adsorbed species and assessment of the role of chemisorbed atoms as active sites for surface recombination. Kinetics of adsorption and desorption processes was studied by varying the duration of plasma exposure. It was found that under direct plasma exposure not only adsorbed atoms but also atoms of the material participate in surface reactions. Oxygen atoms composing the outmost layer of silica-like surfaces are continuously exchanged with the gas phase O and N atoms produced in the discharge.

NW1 76 Reaction model for etching surface interacted with hydrofluorocarbon plasmas KENJI ISHIKAWA, YUSUKE KONDO, YUDAI MIYAWAKI, TOSHIO HAYASHI, MAKOTO SEKINE, KEIGO TAKEDA, HIROKI KONDO, MASARU HORI, *Nagoya University* We report a model for plasma etching on the basis of understanding interactions between hydrofluorocarbon plasmas and dielectric surface. To construct the model, we carried out quadpole mass spectroscopic measurements of cracking patterns with changing electron energy of ionization, and estimated the cross-sections for ionizing dissociation of gases such as CH_xF_{4-x} (x:1-3) molecules. Assuming a electron temperature, rate constants for these reactions were calculated by integrating over whole electron energy range. Next we made comparison in performance for plasma etching among CHF_3, CH_2F_2 and CH_3F gases by measuring densities of both ions and radicals and compared the results of etch rate with the results of the densities of the species in gas phase. For CHF_3, CH_2F_2 and CH_3F molecules, hydrogen atom was dissociated easier than fluorine atom. Cross section is ordered by $CH_3F > CH_2F_2 > CHF_3$. According to the experimental results, the chemical reaction model was constructed and we have evaluated interaction of dielectric surface with hydrofluorocarbon plasmas.

NW1 77 3D feature profile simulation based on realistic surface kinetic studies of silicon dioxide etch process in fluorocarbon plasmas WON-SEOK CHANG, *National Fusion Research Institute* DONG-HUN YU, *Kyung Won Tech.Inc* DEOG-GYUN CHO, YEONG-GEUN YOOK, POO-REUM CHUN, SE-A LEE, *Chonbuk National University* DEUK-CHUL KWON, MI-YOUNG SONG, JUNG-SIK YOON, *National Fusion Research Institute*

YEON-HO IM, *Chonbuk National University* Low pressure fluorocarbon plasmas are commonly used in microelectronics fabrication of plasma etching of dielectric materials. Recently, one of the critical issues in the etching processes of the nanoscale devices is to achieve ultrahigh deep contact hole without anomalous behaviors such as sidewall bowing and twisting profile. To achieve this goal, the fluorocarbon gases have been used to optimize the reactant fluxes and obtain the ideal etch profile. However, the semiconductor industries still suffer from the absence of the robust and predictable modeling tools due to the inherent complex plasma chemistry. As an effort to address this issue, we have developed a 3D topography simulator using the level set algorithm based on new memory saving technique, which is suitable in the contact hole etching. For this feature profile simulation, we performed a fluorocarbon plasma-surface kinetic modeling based on our experimental data, a polymer layer based this model was proposed as considering material balance of deposition and etching through steady-state FC layer. Finally, the modeling results showed good agreements with experimental data and could be used successfully for 3D etch profile simulations with consideration of polymer layer.

NW1 78 POST-DEADLINE ABSTRACTS

NW1 79 Design of an ECR coaxial microwave plasma source using solid state microwave generator LOUIS LATRASSE, MARILENA RADOIU, *SAIREM SAS, 12 Porte du Grand Lyon, 01702 Neyron, Cedex France* Since the use of electrodes in plasma processing presents many disadvantages, e.g. contamination or corrosion, microwaves are frequently used to supply high density plasmas. Stable and reliable microwave plasma equipment based on magnetrons and designed for automatic control of the operating variables has already proved its efficiency in low temperature diamond deposition, exhaust gas abatement, thin film deposition, etc. Large-scale processing with high density and uniform plasma is necessary for surface treatments that need highly uniform etching or deposition rates. To meet these industrial requirements, Sairem has designed a new ECR coaxial microwave plasma source with very high performances in terms of plasma density and working pressure range. Furthermore, each plasma source has its own microwave generator, the solid state generator developed by Sairem, which uses transistor technology. The advantages and the performance of this combination of technology will be reported. For example, plasma scaling up requires to distribute and apply uniform electric field over large areas. Thus, by distributing the plasma sources and by controlling the supply of power of each source, it is now possible to produce large, uniform and high density plasma without scale limitation.

NW1 80 Development of a high-power non-ablative capillary discharge source for plasma-materials interactions studies MICHAEL PACHULIO, FRANCESCO STEFANI, ROGER BENGTSON, LAXMINARAYAN RAJA, *The University of Texas at Austin* We report the development of a new non-ablative high-pressure thermal plasma capillary discharge source for studying plasma-surface materials interactions phenomena under pulsed plasma conditions. A key requirement is to allow for a high degree of control over the composition, power, and energy of the plasma, which is not achievable with classical ablative-liner supported capillary discharges. This paper describes the design and performance of a non-ablative capillary discharge that uses a quartz liner, to produce ~1 eV argon thermal (near-equilibrium) plasma. We describe an approach to reliably ignite the source using a secondary wire electrode that creates a travelling surface discharge along the quartz surface prior to the main discharge event. The argon feedgas contains 2% hydrogen for permitting additional spectroscopic diagnostics of the plasma. Measurements of plasma temperature, plasma density, and power are provided for various configurations of the power supply and capillary which was operated between 4 and 25 kV.

NW1 81 Atmospheric Gaseous Plasma with Large Dimensions SERGEY KORENEV, *Lynntech, Inc.* The forming of atmospheric plasma with large dimensions using electrical discharge typically uses the Dielectric Barrier Discharge (DBD). The study of atmospheric DBD was shown some problems related to homogeneous volume plasma. The volume of this plasma determines by cross section and gas gap between electrode and dielectric. The using of electron beam for volume ionization of air molecules by CW relativistic electron beams was shown the high efficiency of this process [1,2]. The main advantage of this approach consists in the ionization of gas molecules by electrons in longitudinal direction determines by their kinetic energy. A novel method for forming of atmospheric homogeneous plasma with large volume dimensions using ionization of gas molecules by pulsed non-relativistic electron beams is presented in the paper. The results of computer modeling for delivered doses of electron beams in gases and ionization are discussed. The structure of experimental bench with plasma diagnostics is considered. The preliminary results of forming atmospheric plasma with ionization gas molecules by pulsed nanosecond non-relativistic electron beam are given. The analysis of potential applications for atmospheric volume plasma is presented.

[1] S. Korenev, "The ionization of air by scanning relativistic high power CW electron beam," 2002 IEEE International Conference on Plasma Science, May 2002, Alberta, Canada.

[2] S. Korenev and I. Korenev, "The propagation of high power CW scanning electron beam in air," BEAMS 2002: 14th International Conference on High-Power Particle Beams, Albuquerque, New Mexico (USA), June 2002, AIP Conference Proceedings Vol. 650(1), pp. 373–376, December 17.

NW1 82 The Pulsed Cylindrical Magnetron for Deposition SERGEY KORENEV, *Lynntech, Inc.* The magnetron sputtering deposition of films and coatings broadly uses in microelectronics, material science, environmental applications and etc. The rate of target evaporation and time for deposition of films and coatings depends on magnetic field. These parameters link with efficiency of gas molecules ionization by electrons. The cylindrical magnetrons use for deposition of films and coatings on inside of pipes for different protective films and coatings in oil, chemical, environmental applications. The classical forming of magnetic field by permanent magnets or coils for big and long cylindrical magnetrons is complicated. The new concept of pulsed cylindrical magnetron for high rate deposition of films and coating for big and long pipes is presented in this paper. The proposed cylindrical magnetron has azimuthally pulsed high magnetic field, which allows forming the high ionized plasma and receiving high rate of evaporation material of target (central electrode). The structure of proposed pulsed cylindrical magnetron sputtering system is given. The main requirements to deposition system are presented. The preliminary data for forming of plasma and deposition of Ta films and coatings on the metal pipers are discussed. The comparison of classical and proposed cylindrical magnetrons is given. The analysis of potential applications is considered.

SESSION PR1: POSTER SESSION II (8:00-10:00AM)
Thursday Morning, 25 October 2012
Exhibit Salon CDE at 8:00

PR1 1 PLASMA SCIENCE II

PR1 2 Simulation of the OH Emission Molecular Spectrum to Determine the Plasma Temperature and the Influence Noise to Signal Ratio on the Temperature Values HOSSEIN NASSAR, OULOUM AOUDE, *Lebanese University* FSP SECTION IV KARAK-ZAHLET TEAM The OH system ($A^2\Sigma^+$ - $X^2\Pi_I$) molecular emission spectrum is frequently observed in plasma sources containing water. We have simulated the spectrum of (0,0) and (1,1) bands of this system from 3064 Å for different rotational and vibrational temperatures. The influence of the noise to signal ratio has been studied, if the noise to signal ratio is about 10% we found an error of 6% at temperature 3000 K and 10% at 6000 K.

PR1 3 Measuring effective electron temperatures with the argon 420.1-419.8 nm line ratio* JOHN B. BOFFARD, R.O. JUNG, CHUN C. LIN, *Department of Physics, University of Wisconsin-Madison* L.E. ANESKAVICH, A.E. WENDT, *Department of Electrical and Computer Engineering, University of Wisconsin-Madison* We explore the possibility of measuring the effective electron temperature in argon-containing plasmas using the line ratio of the 420.1 nm and 419.8 nm argon emission lines [1]. At high electron temperatures, the upper levels of both transitions are populated mainly by electron-impact excitation of ground state atoms and yield a line ratio near one. At lower electron temperatures, the upper level of the 420.1 nm line (the J=3 $3p_9$ level) is preferentially populated via excitation from the $J = 2$ $1s_5$ metastable level [2], yielding line ratios as high as four. Variations in the energy dependence of the ground state cross sections [3] can also produce line ratios less than one when highly energetic electrons are abundant. We compare temperatures obtained with this single line pair ratio with measurements obtained from an analysis of 20+ $2p_x \rightarrow 1s_y$ emission lines in the 665-1150 nm wavelength range and with Langmuir probe measurements in a number of different plasmas (inductive, capacitive, helicon).

*Supported by NSF grants CBET 0714600 and PHY-1068670.

[1] J. Phys. D **45**, 045201 (2012).
[2] Phys. Rev. A **75**, 052707 (2007).
[3] Phys. Rev. A **68**, 032719 (2003); At. Data Nucl. Data Tables **93**, 831 (2007).

THURSDAY MORNING \ PR1

PR1 4 Distribution and Dynamics of Argon Metastables in Supersonic Flowing Microwave Discharges and Post-Discharges MILKA NIKOLIC, ANA SAMOLOV, CHARLES I. SUKENIK, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Center for Accelerator Science, Old Dominion University* Supersonic flowing microwave discharge in Argon exhibits a peculiar asymmetric post-discharge glow, which is detached from the discharge. We have studied the behavior of 4p Ar states using optical emission tomography and found their strong transversal motion possibly originating from rotational component of the flow [1]. In this work, we have employed Laser Induced Fluorescence (LIF) technique to obtain the excited state populations from the argon spectra in the post-discharge of the supersonic flowing microwave discharge. The experimental set-up consists of a pulsed tunable dye laser operating in the near infrared region and a cylindrical resonance cavity operating in TE111 mode at 2.45 GHz. The microwave discharge was obtained at the pressure of 2.4 Torr and the gas temperature in the post-discharge was gradually decreasing from ~1100 to ~ 800 K. We present the population distributions of 4p states and compare the results between the LIF and OES methods, and the population distributions of the 4s metastable states from LIF measurements.

[1] M. Nikolic, F. Cuckov, A. Samolov, A. Godunov, S. Popovic, and L. Vuskovic, "Tomography as a Diagnostic Tool for Plasma Etching of SRF Cavities," Proc. IPAC, WEPPC104 (2012) (New Orleans, LA).

PR1 5 Development of a Thomson-type Mass and Energy Spectrometer for High-energy Plasma Beams with the Geant4 Monte Carlo Toolkit GREGORY RIEKER, FLAVIO POEHLMANN, *Fluence, LLC* MARK CAPPELLI, *Stanford University* Thomson-type spectrometers characterize particle beams using parallel magnetic and electric fields to separate and detect ions of different mass, energy, and charge state. Traditionally, the output of these spectrometers is calibrated against particle beams of known species and energy, or less accurately, using particle trajectory calculations assuming uniform fields. We present the design and calibration of a Thomson spectrometer using the Geant4 Monte Carlo toolkit. By running Monte Carlo simulations using the precise spectrometer geometry, including the measured non-uniform magnetic field and two dimensional electric field simulations, it is possible to accurately predict and calibrate the output of the spectrometer without a known particle beam. We will describe the application of this spectrometer to the output of an electromagnetic plasma accelerator operating in a gas-puff mode, and quantify the error associated with calibrating the spectrometer assuming uniform fields.

PR1 6 Atmospheric Pressure Plasma Electron Density Measurements by Magnetohydrodynamic Generator (MHDG) Method ALI GULEC, FERHAT BOZDUMAN, ERDOGAN TEKE, LUTFI OKSUZ, *Suleyman Demirel University* In this work atmospheric pressure plasma discharge was immersed in a hollow box which is called as manetohydrodynamic generator (MHDG). This box consists of two conductors and two insulating edges. Permanent magnets were placed on the insulating edges for a magnetic field which is perpendicular to the discharge flow. Hall-effect voltage was observed between the opposite conductive edges of the MHDG. 1 kHz atmospheric pressure helium discharge density was calculated as 4.9×10^{13} cm^{-3} by using Hall-effect voltage and the discharge current. For different plasma conditions plasma density calculations will be given.

PR1 7 Non-intrusive measurements of ion fluxes and densities in pulsed RF plasmas containing nanoparticles* I. STEFANOVIC, *Exp. Phys. II, Ruhr-Universitaet Bochum, Germany* B. SIKIMIC, *Exp. Phys. II, Ruhr Universitaet* I. DENYSENKO, *Kharkiv National University Ukraine* J. WINTER, *Exp. Phys. II, Ruhr Universitaet* EXPERIMENTAL PHYSICS II BOCHUM TEAM, I. DENYSENKO, KHARKIV NATIONAL UNIVERSITY COLLABORATION Electrical probe measurements are widely spread for diagnostics of low-pressure plasmas. However, the probe measurements in plasmas for thin film deposition and nanoparticle formation are difficult. Thin film on the probe surface changes the probe characteristics and thus obscures the results. The probe tip disturbs locally the dust particle density and consequently the ion and electron flux to the probe. Braithwaite *et al.* developed the electrostatic probe method that proved as tolerant for thin film deposition, although the disturbance caused by the inserted probe should be taken into account. Following the ideas of Braithwaite *et al.* we developed the diagnostics for measuring the ion-current and ion density in pulsed RF plasmas with and without nanoparticles. The technique bases on measurement of electrode self-bias voltage thus avoiding plasma perturbation. The rate of voltage change can be attributed to the ion current to the electrode in the afterglow. Assuming the Bohm velocity of ions in the afterglow the ion density can be calculated. We compare and discuss the ion densities obtained like described with the independently measured electron densities for dust free and dusty argon plasma.

*Humbodt Foundation

[1]N. St. Braithwaite *et al.*, Plasma Sources Sci. Technol. **5**, 677 (1996).

PR1 8 Measurements of the energies of negative ions produced in processing plasmas DAVID SEYMOUR, CLAIRE GREENWOOD, SEAN DAVIES, ALAN REES, *Hiden Analytical* HIDEN ANALYTICAL TEAM The quality of the thin oxide films deposited on a variety of materials during exposure to plasmas containing oxygen depends strongly on the identity and energies of the negative oxygen ions arriving at the growing films. There have, however, been few experimental studies in which these ion energies have been measured and the available data is markedly less abundant than for the corresponding positive ions. We discuss reasons for the lack of data and suggest suitable techniques for obtaining energy distributions for mass identified ions for a variety of plasmas, including both steady-state and pulsed DC and RF plasmas. For asymmetric RF plasmas the distributions depend on the relative dimensions of the sheath regions in front of the discharge electrodes, whereas for DC magnetron systems a dominant parameter is the voltage applied to the magnetron cathode, particularly when this is pulsed. Sample data for O-, O2-, and O3-ions are shown for mixtures of oxygen and argon for a number of systems including a DC plasma system in which the ions were sampled through an orifice in the anode electrode, and a small magnetron device for which the ions arriving at a grounded substrate were observed.

PR1 9 On-axis Molecular Beam Mass Spectrometer measurements of a cold atmospheric pressure plasma jet* JOERN WINTER, MARIO DUENNBIER, MARKUS WOLFRAM, ANSGAR SCHMIDT-BLEKER, *ZIK plasmatis at the INP Greifswald e.V.* KLAUS-DIETER WELTMANN, *INP Greifswald* STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* The measured on-axis molecular species densities in the effluent of a cold plasma jet operated at atmospheric pressure were performed for different distances (3...35 mm) with a molecular beam mass spectrometer (MBMS) (Hiden HPR 60). The investigated molecules are nitrogen ($M = 28$ u), oxygen ($M = 32$ u) and argon ($M = 40$ u). A stainless steel orifice with a diameter of 100 μm in front of the first pump stage was used. After a calibration of the intensities of the mass spectrometer the absolute densities were calculated. These values are compared with a model of the gas flux and show excellent agreement. It is shown that because of the feed gas flow of the plasma jet the ambient air species (e.g. N_2 and O_2) are displaced in the case of small distances. For larger distances the diffusion of nitrogen and oxygen molecules into the effluent increases. Effects of composition distortion and pressure dependencies inside the MBMS were observed in the calibration curve and were taken into account.

*This work was funded by German Ministry of Education and Research (grant number: 03Z2DN12).

PR1 10 Diagnostic of plasma jet by mid-IR absorption spectroscopy with quantum cascade laser* SYLVAIN ISENI, MARIO DUENNBIER, JOERN WINTER, *ZIK plasmatis at the INP Greifswald e.V.* KLAUS-DIETER WELTMANN, *INP Greifswald e.V.* STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* The interest in plasma jets operating at atmospheric pressure have considerably grown during the last decade. The non-equilibrium properties of the discharge enhances specific and interesting chemistry especially that of reactive nitric-oxide species (RNOS) such as O_3 or NO. It is already known that for instance O_3 has biological effects and have been used for sterilization of non-living objects. Thus, in order to investigate and control the biological reactive species produced by the jet, very accurate techniques are required. By using absorption spectroscopy in the mid-infrared range with quantum cascade laser, we were able to measure very accurate absolute production rates. The spectral range is restricted to the so-called fingerprint area (500–1500 cm^{-1}). Many approaches have been made to overcome the spectroscopic problems of the pressure broadening. One of those consists of simulating the spectrum online and then calculates the concentration by fitting the measurement with the simulation. We can assume an accuracy of 200 ppb with a lowest detection limit of 300 ppb. The diagnostic of O_3 is led on a MHz radiofrequency plasma jet operating with argon. The O_3 production is also compared regarding different admixtures such as O_2, N_2 or H_2O and surrounding atmosphere.

*German Ministry of Education and Research (BMBF, grant number 03Z2DN12).

PR1 11 Transmission characteristics of the wave cut-off probe with parallel plates HYUN-JU KANG, YU-SIN KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* A cut-off probe has been used to obtain an absolute electron density from a plasma frequency. A cut-off probe with parallel plates was constructed to investigate the transmission characteristics of electromagnetic waves and electrostatic waves at various gaps, pressures and powers. It is found that a clear cut-off peak at a plasma frequency and many other peaks due to plasma sheath series resonance, cavity resonance and transmission line are observed. By using circuit model of plasma and transmission line theory, the various peaks was analyzed and discussed.

PR1 12 Non-invasive, real-time measurements of plasma parameters with an industry standard spectrograph* SHICONG WANG, A.E. WENDT, *Department of Electrical and Computer Engineering, University of Wisconsin-Madison* JOHN B. BOFFARD, CHUN C. LIN, *Department of Physics, University of Wisconsin-Madison* SVETLANA RADOVANOV, HAROLD PERSING, *Applied Materials Inc., Varian Semiconductor Equipment Business Unit, 35 Dory Road, Gloucester, MA 01939 USA* Plasma process control applications require acquisition of diagnostic data at a rate faster than the characteristic timescale of perturbations to the plasma. Diagnostics based on optical emission spectroscopy (OES) of intense emission lines permit rapid non-invasive measurements with low-resolution (~1 nm), fiber-coupled spectrographs, included on many plasma process tools for semiconductor processing. Here we report on rapid analysis of Ar($3p^54p \rightarrow 3p^54s$) 650–800 nm emissions with such a system to obtain electron temperatures and metastable densities in argon and argon/mixed-gas (Ar/N_2, Ar/O_2, Ar/H_2) inductively coupled plasmas. The OES-derived values are compared to measurements made by electric probes, white-light absorption spectroscopy, and OES measurements made with a high-resolution 0.5 m spectrometer. In a pure Ar plasma, for example, we have measured the metastable densities to better than $\pm 15\%$ accuracy within 0.25 seconds. A number of subtraction procedures have been evaluated to extract the Ar emission intensities in the presence of overlapping molecular emissions. This is especially necessary for Ar/N_2 plasmas, which feature intense N_2 molecular emissions in the wavelength range of interest.

*Supported by NSF grant PHY-1068670.

PR1 13 Collisionless spectral-kinetic Simulation of the Multipole Resonance Probe WLADISLAW DOBRYGIN, DANIEL SZEREMLEY, CHRISTIAN SCHILLING, JENS OBERRATH, DENIS EREMIN, THOMAS MUSSENBROCK, RALF PETER BRINKMANN, *Institute for Theoretical Electrical Engineering, Ruhr University Bochum, 44780 Bochum, Germany* Plasma resonance spectroscopy is a well established plasma diagnostic method realized in several designs. One of these designs is the multipole resonance probe (MRP). In its idealized - geometrically simplified - version it consists of two dielectrically shielded, hemispherical electrodes to which an RF signal is applied. A numerical tool is under development, which is capable of simulating the dynamics of the plasma surrounding the MRP in electrostatic approximation. In the simulation the potential is separeted in an inner and a vacuum potential. The inner potential is influenced by the charged partilces and is calculated by a specialized Poisson solver. The vacuum potential fulfills Laplace's equetion and consists of the applied voltage of the probe as boundary condition. Both potentials are expanded in spherical harmonics. For a practical particle pusher implementation, the expansion must be appropriately truncated. Compared to a PIC simulation a grid is unnecessary to calculate the force on the particles. This work purpose is a collisionless kinetic simulation, which can be used to investigate kinetic effects on the resonance behavior of the MRP.

[1]M. Lapke *et al.*, Appl. Phys. Lett. **93**, 051502 (2008).

PR1 14 Heavy Neutral Beam Probe Space Potential Measurements of the Helimak Experiment (Te ~ 10 eV) ALVARO GARCIA DE GORORDO, GARY A. HALLOCK, KENNETH W. GENTLE, *The University of Texas at Austin* The Heavy Neutral Beam Probe (HNBP) for the Helimak low temperature plasma experiment has been developed at the University of Texas at Austin (UT-Austin). The HNBP is based on the highly successful Heavy Ion Beam Probe (HIBP), but is engineered to work in the low temperature plasma regime ($T_e < 40$ eV). The greatest difficutly to operation at low electron temperatures is that the measurement signal is enabled by electron-impact ionization events, which become increasingly rare when the temperature dips to ~ 10 eV. This problem is overcome by probing the plasma with a neutral alkali metal (Na) and by modulating the probing beaming with a square wave (chopping) and recovering the signal with phase sensitive detection. The Helimak experiment at UT-Austin approximates the infinite cylindrical slab with open field lines1. The geometry is like a torus, but with a rectangular cross-section and with vertical field coils, that combined with the toroidal field coils, give rise to a helical magnetic field inside the device. Because of the curved, sheared magnetic field, and its gradient, the Helimak simulates the scrape off layer (SOL) of a tokamak.

PR1 15 Spatial distributions measurement of negative ion density by using floating probe in the oxygen inductive coupled plasmas HYE-JU HWANG, YU-SIN KIM, *Department of Electrical Engineering, Hanyang University* YOUNG-CHOEL KIM, JUNYOUNG KIM, *Department of Nano-scale Semiconductor Engineering, Hanyang University, Seoul, Korea* IL-SEO PARK, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Spatial distributions of the negative ion density were measured in an oxygen inductive discharge from the measurement of the positive ion density and electron density by using a floating harmonic method [1]. When the probe was electrically floated by a direct current (DC) blocking capacitor, the positive ion density was measured, while the electron density was measured without the DC blocking capacitor. Thus, the spatial negative ion density distribution could be obtained from the measurement of the spatial difference between the positive ion density and the electron density. The spatial distributions of negative ion density from two single Langmuir probe consist of planar and cylindrical probe tip are compared with those by our method for the reliability.

[1]M. H. Lee, S. H. Jang, and C. W. Chung, J. Appl. Phys. **101**, 033305 (2007).

PR1 16 Characterization of pulsed plasma jets by wave front distortion analysis BENJAMIN WANG, FLAVIO POEHLMANN, MARK CAPPELLI, *Stanford University* Wave front distortion analysis is a non-perturbing plasma diagnostic technique used to measure the refraction of probing laser beams due to density gradients in the medium. A Shack-Hartmann wave-front sensor consisting of a micro-lenslet array coupled to a CCD sensor was used to characterize a pulsed co-axial discharge plasma jet experiment. A pulsed laser beam was passed through the plasma jet and the refraction angles of the beam as a result of the complex refractive index of the plasma were measured using a Shack-Hartmann wave front sensor. For axially-symmetric plasmas, an Abel inversion of the refraction angle data allows for the calculation of the line-integrated electron density gradient profile of the plasma jet. Wave front distortion measurements were also calculated from the refraction angle data.

PR1 17 Kinetics of Electrons in Ar/BF_3 Mixtures* ZELJKA NIKITOVIC, VLADIMIR STOJANOVIC, *Institute of Physics, Belgrade, Serbia* SVETLANA RADOVANOV, *Varian Semiconductor/SSG/Applied Materials, 35 Dory Road, GL-17, Gloucester, MA01930 USA* ZORAN LJ. PETROVIC, *Institute of Physics, Belgrade, Serbia* In this work we present electron transport coefficients in Ar/BF_3 mixtures for the conditions used in plasma assisted technologies for semiconductor production. Transport coefficients are used as the basis for a global model in Ar/BF_3 mixtures. We have used a two term numerical solution of the Boltzmann equation and also performed exact calculations using a Monte Carlo simulation. We have calculated electron transport coefficients for a binary mixture of 90% Ar with 10% of BF_3. Similar mixtures are often used in plasma assited ion implantation applications. In order to determine the role of radicals on kinetics, we have added 1% of radical species F and F_2. The effect of radicals on electron kinetics is relatively small for abundances below 1%. For higher abundances all transport coefficients, mean energies and rate coefficients are affected to a degree which could affect the operating conditions in plasmas.

*Results obtained in the Laboratory of Gaseous Electronics Institute of Physics University of Belgrade under the auspices of the Ministry of Education and Science, Projects No. 171037 and 410011.

PR1 18 2D and 3D PIC-MCC simulations of a low temperature magnetized plasma on CPU and GPU* JONATHAN CLAUSTRE, BHASKAR CHAUDHURY, GWENAEL FUBIANI, JEAN-PIERRE BOEUF, *LAPLACE, Universite de Toulouse, France* A Particle-In-Cell Monte Carlo Collisions model is used to described plasma transport in a low temperature magnetized plasma under conditions similar to those of the negative ion source for the neutral beam injector of ITER. A large diamagnetic electron current is present in the plasma because of the electron pressure gradient between the ICP driver of the source and the entrance of the magnetic filter, and is directed toward the chamber walls. The plasma potential adjusts to limit the diamagnetic electron current to the wall, leading to large electron current flow through the filter, and to a non uniform plasma density in the region between magnetic filter and extracting grids. On the basis of the PIC-MCC simulation results, we describe the plasma properties and electron current density distributions through the filter in 2D and 3D situations and use these models to better understand plasma transport across the filter in these conditions. We also present comparisons between computation times of two PIC-MCC simulation codes that have been developed for operations on standard CPU (Central Processing Units, code in Fortran) and on GPU (Graphics Processing Units, code in CUDA). The results show that the GPU simulation is about 25 times faster than the CPU one for a 2D domain with 512x512 grid points. The computation time ratio increases with the number of grid points.

*Work supported by Federation de Recherche FM, and by Universite P. Sabatier, MOSITER project.

PR1 19 Electronegative Plasma Equilibria with Spatially-Varying Ionization* M.A. LIEBERMAN, E. KAWAMURA, A.J. LICHTENBERG, *UC Berkeley* Electronegative inductive discharges in higher pressure ranges typically exhibit localized ionization near the coil structure, with decay of the ionization into the central discharge. We use a two-dimensional fluid code [1] with chlorine feedstock to determine the spatial profiles of the plasma parameters in a cylindrical transformer-coupled plasma device excited by a planar coil. To compare with one-dimensional (1D) analytic modeling, the results are area-averaged. The ionization is found to decay roughly exponentially along the axial direction, allowing the ansatz of an exponentially decaying ionization to be used in a 1D computational model. The model captures the main features of the axial variations of the area-averaged fluid simulation, indicating that the main diffusion mechanisms act along the axial direction. A simple analytic global discharge model is developed, accounting for the asymmetric density and ionization profiles. The global model gives the scalings with power and pressure of volume-averaged densities, electron temperature, and ionization decay rate, also in reasonable agreement with the scalings obtained by averaging the simulation results.

*Department of Energy Office of Fusion Energy Science Contract DE-SC000193.

[1] E. Kawamura, D.B. Graves, and M.A. Lieberman, Plasma Sources Sci. Technol. **20**, 035009 (2012).

PR1 20 Space-Charge Limitations in Photon-Enhanced Thermionic Emission and Possible Solutions TSUYOHITO ITO, *Osaka University* MARK CAPPELLI, *Stanford University* Traditionally, thermionic energy conversion is most efficient at high temperatures (>1500 K). In a recent study [J.W. Schwede *et al.*, Nature Materials 9, 762 (2010)], photon-enhanced thermionic emission (PETE) from semiconducting cathodes was shown to be a promising means of increasing the thermionically-driven cathode current density at relatively low cathode temperatures (500–1100 K). However, at the high emitted current densities described in Ref. 1 (3 – 30 A/cm^2), one might expect that the electron transport will be space-charge limited. In this presentation, using a particle-in-cell (PIC) method, we simulate the PETE energy converter to clarify these space charge effects, and also to provide a possible solution to overcoming the limitation using an optically-produced non-equilibrium Cs plasma.

PR1 21 Hybrid modelling of a DC glow discharge with an analytical ionization source term of fast electrons* ANATOLY KUDRYAVTSEV, EUGENE BOGDANOV, *St. Petersburg State University* ISMAIL RAFATOV, *Middle East Technical University, Ankara, Turkey* In any type of existing fluid model ("simple", "extended" and so on) the electron ensemble is considered as a whole and is characterized by the averaged parameters, namely, the averaged density, averaged energy (temperature), and averaged directional drift velocity. However, in reality the EDF in the near-cathode region is nonlocal, such that the different electron groups (especially the fast electrons emerged from the cathode layer) behave differently and separate from each others. Accordingly, they cannot be described by averaged parameters and kinetic analysis is needed. We developed and tested a simple hybrid model for a glow discharge, which incorporates nonlocal ionization by fast electrons into the fluid framework, and thereby overcomes the fundamental shortcomings of the fluid model. At the same time, proposed model is computationally much more efficient compared to the models involving Monte Carlo simulations. Calculations have been performed for an argon gas. Comparison with the experimental data as well as with the hybrid (particle) and fluid modelling results demonstated good applicability of the proposed model.

*The work was supported by the joint research grant TUBITAK and RFBR.

PR1 22 Kinetic modeling of electronically enhanced reaction pathways in Plasma Assisted Combustion* GUY PARSEY, YAMAN GÜÇLÜ, JOHN VERBONCOEUR, ANDREW CHRISTLIEB, *Michigan State University* The use of plasma energy to enhance and control the chemical reactions during combustion, a technology referred to as "plasma assisted combustion" (PAC), can result in a variety of beneficial effects: e.g. stable lean operation, pollution reduction, and wider range of p-T operating conditions. While experimental evidence abounds, theoretical understanding of PAC is at best incomplete, and numerical tools still lack in reliable predictive capabilities. In the context of a joint experimental-numerical effort at Michigan State University, we present here a modular Python framework dedicated to the dynamic optimization of non-equilibrium PAC systems. We first describe a novel kinetic global model, which aims at exploring scaling laws in parameter space, as well as the effect of a non-Maxwellian electron energy distribution function (EEDF). With such a model, we reproduce literature results and we critically review the effect of data uncertainty and limiting assumptions. Then, we explore means of measuring a non-Maxwellian EEDF through the use of a detailed collisional-radiative model, coupled to optical emission spectroscopy. Finally, we investigate the effect of different numerical integrators, as well as customized routines specifically designed to solve stiff sparse ODE systems.

*Supported by AFOSR and a Michigan State University Strategic Partnership Grant.

PR1 23 Simulation of a capacitively coupled oxygen discharge using the oopd1 particle-in-cell Monte Carlo code J.T. GUDMUNDSSON, *Shanghai Jiao Tong University* M.A. LIEBERMAN, *University of California at Berkeley* The oopd1 particle-in-cell Monte Carlo (PIC-MC) code is used to simulate a capacitively coupled discharge in oxygen. oopd1 is a one-dimensional object-oriented PIC-MC code in which the model system has one spatial dimension and three velocity components. It contains models for planar, cylindrical, and spherical geometries and replaces the XPDx1 series, which is not object-oriented. The revised oxygen model includes, in addition to electrons, the oxygen molecule in ground state,the oxygen atom in ground state, the negative ion O^-, and the positive ions O^+ and O_2^+. The cross sections for the collisions among the oxygen species have been significantly revised from earlier work using the XPDP1 code. Here we explore the electron energy distribution function (EEDF), the ion energy distribution function (IEDF) and the density profiles for various pressures and driving frequencies. In particular we investigate the IEDF for both O^+ and O_2^+ ions for various discharge conditions. We explore the role of fragmentation due to collisions of high energy O_2^+ ions with oxygen molecules its influence on the IEDF for O^+-ions.

PR1 24 Modeling of low temperature plasma for FOUP cleaning* DIANA MIHAILOVA, GERJAN HAGELAAR, PHILIPPE BELENGUER, *LAPLACE, CNRS and Univ. Toulouse, France* PHILIPPE GUILLOT, LAURENT THERESE, BRUNO CAILLIER, *DPHE, Centre Universitaire J.F. Champollion, Albi, France* The contamination control in the processing stages in semiconductor industry is a major issue for the microelectronics yield and performance, as well as for the development of new technologies in the area. This mainly concern the wafer carrier boxes (FOUP), which typically provide environmental isolation, clean and secure wafer transport. However, molecule or wall contamination inside the carrier box, can strongly affects the production processes. The goal of this research is to find an efficient solution for decontamination of the FOUP by generating an uniform low temperature plasma inside the box. Various types of plasma are considered with the main task of cleaning using the plasma fluxes directed to the walls and in the same time not damaging the surfaces. In order to apply and test different types of plasma we make use of numerical modeling. The first studied type of plasma is a capacitive RF plasma generated inside a closed box. A time dependent 2 dimensional multi-fluid model is constructed in order to study the plasma behavior and plasma properties. The model is applied to a simplified 2D geometry with pure Ar gas. The influence of various parameters are studied and preliminary results are presented.

*This work is supported by OSEO, ISI project "PAUD."

PR1 25 Particle based 3D modeling of streamer discharges JANNIS TEUNISSEN, ANBANG SUN, CHAO LI, *Centrum Wiskunde & Informatica* UTE EBERT, *Centrum Wiskunde & Informatica, Eindhoven University of Technology* Streamers are rapidly growing plasma channels surrounded by a thin space-charge layer. They pave the way for sparks and lightning leaders, and they have many applications in plasma technology. There are fundamental open questions concerning streamers: Under what conditions do they emerge from electrodes? What determines properties like radius and velocity? When do they start to branch? To help answer these questions we have developed a 3D particle simulation with adaptive mesh refinement and dynamic particle control. This allows us to explore the full physics of streamer formation and initial propagation. We explain the modeling technique, present simulation results and discuss their implications.

PR1 26 3D Spatially hybrid model for streamer discharge ANBANG SUN, JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica* UTE EBERT, *Centrum Wiskunde & Informatica, Eindhoven University of Technology* Streamers are rapidly growing plasma filaments. They play an important role in the early stages of lightning, as well as in industrial application such as lighting, plasma assisted combustion and disinfection. In previous work, the first generation of 3D spatially hybrid codes was developed by Chao Li, to study the propagation of negative streamer without photoionization in a background field above the breakdown value. We now have set up the second generation codes to improve and optimize the original program, and to make it accessible. Adaptive Mesh Refinement and parallel computing technique are being adopted as well, to increase the accuracy, efficiency and parameter range of simulations. The codes are being used to study the streamers emergence from the inception cloud, streamers branching and feather formation in different N2:O2 ratios, and streamers interaction.

PR1 27 Secondary electron emission induced by fast argon neutrals and its effects on rf plasmas ALEKSANDAR BOJAROV, MARIJA RADMILOVIC-RADJENOVIC, ZORAN LJ. PETROVIC, *Institute of Physics Belgrade* In this paper we have examined a dual-frequency rf discharge in argon that is strongly affected by the secondary emission of electrons from the electrodes. We have used implicit "Particle In Cell" code as a tool for investigation of different electrode surface conditions that define the secondary emission. For precise description of the secondary emission we use analytic formulas suggested by Phelps and Petrovic (Plasma Sources Sci. Technol 8, R21, 1999). Two surface conditions, atomically "clean" and "dirty," describe the secondary emission as a function of the energy of impacting ion or atom on the electrode. In dual-frequency discharges one of the electrodes usually has some voltage bias, thus leading to greater production of fast neutrals on its side. Since on the biased electrode ion and neutral fluxes are greater than on the powered electrode, the secondary emission from biased electrode has a greater effect on the plasma. Results from our simulations show that secondary emitting fast neutrals can greatly affect the plasma, especially in discharges with intense production of neutrals in the sheath. We conclude that for precise description of rf discharges a realistic modeling of the secondary emission induced by ions and fast neutrals is necessary.

PR1 28 2D Fluid/Analytical Simulation of MultiFrequency Capacitively Coupled Reactor* E. KAWAMURA, M.A. LIEBERMAN, D.B. GRAVES, A.J. LICHTENBERG, *University of California Berkeley* A fast 2D hybrid fluid-analytical multi-frequency capacitively-coupled plasma (CCP) argon reactor model was developed using the finite elements simulation tool COMSOL. The fluid-analytical code was also coupled to a particle-in-cell (PIC) code to obtain the ion energy and angular distribution (IED and IAD) at the wafer. A typical simulation takes less than an hour on a moderate 2.3 GHz, 8GB DRAM worksation. A bulk fluid plasma model is coupled with an analytical sheath model, where an actual vacuum sheath of variable thickness is modeled with a fixed-width sheath of variable dielectric constant. A gas flow model solves for the steady-state pressure, temperature and velocities of the neutrals. The analytical multi-frequency sheath model results were compared to PIC simulations, showing good agreement. By varying the reactor parameters such as input power for each frequency, pressure, discharge gap, wafer electrode radius, etc., we can observe the effect on the plasma density and uniformity as well as the IED and IAD.

*This work was partially supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC000193 and by gifts from Micron Corporation and Lam Research Corporation.

PR1 29 Gyrokinetic Simulation for the Advanced Plasma Source* BENJAMIN SCHROEDER, RALF PETER BRINKMANN, *None* This contribution presents a model based on gyrokinetic theory. The model can be applied to the "Advanced Plasma Source" by Leybold Optics and similar sources that are used for Plasma Ion Assisted Deposition (PIAD) of optical coatings. The source consists of an electron emitting lanthanum hexaboride cathode surrounded by a copper anode and a solenoid that generates an axissymmetric magnetic field of around 25mT. The pressure is typically 0.02 Pa. The electron mean free path exceeds the discharge dimension so that a kinetic model has to be applied. A kinetic equation is derived from Boltzmann's equation and describes the non-local behaviour along the magnetic field lines and diffusion across these. The numerical solution of the equation using different boundary conditions is presented.

*The support by the BMBF within the scope of the PluTO project is gratefully acknowledged.

PR1 30 Study of excitation and emission features in low pressure electronegative oxygen discharges with special regard to the actual electrode surface condition* ARTHUR GREB, KARI NIEMI, DEBORAH O'CONNELL, TIMO GANS, *York Plasma Institute, University of York, YO10 5DD, York, UK* The presented study is based on a one-dimensional semi-kinetic fluid modelling approach, which accounts for a geometrical asymmetry of the radio frequency driven capacitively coupled oxygen plasma. The plasma is operated at a pressure of 40 Pa and with a sinusoidal driving voltage of 300 V amplitude. A simple plasma chemistry is accounted for including electrons, molecular oxygen positive ions (O_2^+), atomic oxygen negative ions (O^-) and metastable singlet delta oxygen ($O_2(^1\Delta)$). The actual electrode surface condition, which strongly affects the plasma-surface interaction processes, is varied in the model by means of changing the secondary electron emission yield from positive ions and the surface loss probability of metastable singlet delta oxygen. It is found that both factors significantly affect plasma parameters, such as the metastable concentration, electronegativity, spatial particle distribution as well as the excitation and ionization dynamics. Excitation pattern generated from simulations are then used to calculate the optical emission signal, which can directly be compared with phase resolved optical emission spectroscopy measurements. By correlating both simulations and experimental measurements plasma and electrode surface parameters can be predicted.

*The authors would like to thank Intel Ireland, Ltd. for supporting this research.

PR1 31 Particle simulation of a micro inductively coupled plasma source including an external circuit YOSHINORI TAKAO, MASATAKA SAKAMOTO, KOJI ERIGUCHI, KOUICHI ONO, *Department of Aeronautics and Astronautics, Kyoto University, Japan* A numerical study of micro inductively coupled plasma (ICP) sources has been conducted. We employ a two-dimensional axisymmetric particle-in-cell with Monte Carlo collisions (PIC-MCC) method, where a transformer model including the effect of capacitive coupling is incorporated. The plasma source is 5 mm in radius and 10 mm in length with a 5-turn helical coil around a cylindrical quartz chamber, where the Ar and Xe plasmas are excited. The simulation was performed for pressures in the range 1–500 mTorr and rf frequencies in the range 1–500 MHz at rf powers less than 10 W. The results indicated that capacitive coupling dominated over inductive coupling and the most of the rf power was deposited in the bulk area at high pressures while the power was absorbed in the sheath area at low pressures. On the other hand, the circuit model was also applied to a conventional large ICP source, and then the result showed that inductive coupling dominated over capacitive coupling. The micro ICP would be E-mode dominated plasmas under the present conditions.

PR1 32 Kinetics of Electrons in H_2O at High Values of Reduced Electric Field* ZORAN PETROVIC, JELENA SIVOS, DRAGANA MARIC, NIKOLA SKORO, VLADIMIR STOJANOVIC, *Institute of Physics, University of Belgrade, P.O.BOX 68 11000 Belgrade, Serbia* In this work we present electron transport coefficients in H_2O for the conditions used in plasma assisted technologies. Monte Carlo technique, already used for similar discharges in nitrogen, argon and hydrogen is used to obtain transport parameters for a range of reduced electric field values (E/N=100-10 kTd). In this work we focus on anisotropic scattering of electron transport and its effects on spatially resolved emission. Agreement with experimental data for electron drift velocity and effective electron ionization for the conditions of moderate E/N allowed us to study production of heavy particles and subsequently spatial emission as a consequence of their transport.

*Results obtained in the Laboratory of Gaseous Electronics Institute of Physics University of Belgrade under the auspices of the Ministry of Education and Science, Projects No. ON171037 and III410011.

PR1 33 Study of atmospheric pressure discharges with a novel hybrid code DENIS EREMIN, TORBEN HEMKE, RALF-PETER BRINKMANN, THOMAS MUSSENBROCK, *Ruhr-Universität Bochum* Numerical simulations bear special significance in helping to understand the phenomena taking place in the atmospheric discharges as the diagnostic capabilities are severely limited there due to small sizes of such discharges. In this work we study atmospheric pressure discharges with a fully self-consistent hybrid code, where the kinetically treated electron component is calculated on GPU using the PIC/MCC approach and ions are treated under the fluid approximation on CPU. The resulting code is fast, because the computationally intensive kinetic algorithm is parallelized on GPU, flexible, because it is straightforward to include complex chemistry processes for the ion component in the fluid model, and allows to capture all the essential physics due to quite general assumptions underlying the model. A comparison with fully fluid simulations is made. We demonstrate with our code that the kinetic description of electrons is important even for the atmospheric pressure discharges.

PR1 34 Optimization of an electron beam exciter via plasma fluid model simulation* DAVID URRABAZO, STEPHAN THAMBAN, *University of Texas at Dallas* JIMMY HOSCH, *Verity Instruments* MATTHEW GOECKNER, *University of Texas at Dallas* There are numerous computational models that can be used to study plasmas, each with advantages and disadvantages. Two of the most commonly used are the ambipolar model and the classical fluid model. The ambipolar model takes advantage of the ambipolar approximation, while the classical model includes the solving of the Poisson's equation. Both models were used to simulate the operation of the ICP electron source of the Electron Beam Exciter. Process conditions and geometrical variations were performed to optimize the electron density and electron to ion ratio in the beam extraction region. Results of this optimization along with deviations between the two models will be presented.

*Verity Instruments and National Science Foundation.

PR1 35 3D CFDTD PIC/Fluid Hybrid Simulations on Plasma Processing of Materials M.C. LIN, *Tech-X* In this work, we propose to use a hybrid method to numerically model the plasma processing of materials including a magnetron sputtering, inductively coupled plasmas (ICPs), capacitively coupled plasmas (CCPs), and microwave plasma enhanced chemical vapor deposition (MPECVD) reactors for getting more physics insight in these plasma processes and better understanding. The neutral atoms in the weakly ionized plasma are represented by a fluid model and the plasma and externally applied fields are described by particle-in-cell (PIC) macro-particles evolving with a conformal finite-difference time-domain (CFDTD) method. Here, we will demonstrate the CFDTD PIC/fluid hybrid simulations of the plasma processing including a magnetron sputtering, an ICP, a CCP, and an MPECVD. All these simulation models are based on the experiments and are still under study and development in collaborating with the experimentalists in industry and academia.

PR1 36 Development of a New Industry Focused Plasma Simulation Tool ADAM WILLIAMS, *University College London* SERGIO LÓPEZ-LÓPEZ, *Quantemol Ltd.* DEREK MONAHAN, WILL BRIGG, JONATHAN TENNYSON, *University College London* Plasma processes are routinely used in a number of industrial settings. However, in the majority of these cases the techniques and procedures used to create the required plasma are determined by experimental trial and error. This advancement has been led in a large part by the technical ability of the engineers in charge of the processes. This mode of operation has largely worked thus far, however, with more complex plasma chemistries being developed and the continual drive for efficiency, simulations are rapidly becoming another instrument in the process engineer's toolset. This poses interesting requirements on any simulation software which is aimed toward industry, such as: ease of use/automation, robust chemistry libraries, simulation speed and reliability. It is the goal of this new project at UCL and Quantemol Ltd. to tackle these issues and more, by developing a simulation tool specifically targeted to industrial applications. This new software will allow the simulation of fully 3D geometries, implementing an automatically refined finite element method (FEM) to solve the appropriate fluid equations, coupled with kinetic simulation methods to improve model efficacy.

PR1 37 The effect of electrode diameter on the ignition of the dc discharge in nitrogen VALERIY LISOVSKIY,* VALERIY MALINOVSKIY, VERONIKA KOVAL, VLADIMIR YEGORENKOV, *Kharkov National University, Svobody Sq.4, Kharkov 61022, Ukraine* This report studied the effect of electrode diameter (55 mm, 25 mm, 12 mm, 5 mm, 2.4 mm and 0.8 mm) on the ignition of the discharge in nitrogen and its modes of burning. The decrease in the electrode diameter was found at large gas pressure values to discharge ignition at lesser voltage values than for large size electrodes and at low gas pressure values to the shift of breakdown curves to higher breakdown voltage values. All breakdown curves we had registered intersected at the nitrogen gas pressure value of $p = 0.9$ Torr close to the inflection point of the breakdown curves for large electrodes. To the left of the inflection point the distortion of the uniform distribution of the electric field between the electrodes of moderate diameter impedes the ionization multiplication within the discharge gap and the breakdown voltage grows, and to the left of the inflection point the conditions for gas breakdown became easier to meet due to the redistribution of the electric field.

*and Scientific Center of Physical Technologies, Svobody Sq.6, Kharkov 61022, Ukraine.

PR1 38 Axial structure of dc glow discharge negative glow in nitrogen VALERIY LISOVSKIY,* VERONIKA KOVAL, EKATERINA KRAVCHENKO, VLADIMIR YEGORENKOV, *Kharkov National University, Svobody Sq.4, Kharkov 61022, Ukraine* This paper reports the studies with a Langmuir probe technique of axial plasma parameters such as electron temperature, potential, electric field and plasma concentration of dc glow discharge negative glow in nitrogen at different gas pressure values. Electron temperature in the negative glow decreases from the cathode sheath boundary and it approaches the smallest value at the anode end of the negative glow. Along the negative glow the plasma potential lowers by about 5 V. Axial profile of plasma concentration possesses a maximum in the negative glow near the cathode sheath boundary similar to the case of low pressure. Along the negative glow the plasma concentration decreases by about 16 times and it approaches its minimum in the transition region to the Faraday dark space. Note that the plasma concentration decrease by 15-16 times was observed at all nitrogen pressure and discharge current values when the negative glow completely found its place within the inter-electrode gap.

*and Scientific Center of Physical Technologies, Svobody Sq.6, Kharkov 61022, Ukraine.

PR1 39 Study of NO formation in a low pressure air-like plasmas at single pulse operation SERGEJ GORCHAKOV, MARKO HÜBNER, JÜRGEN RÖPCKE, DETLEF LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* DANIIL MARINOV, OLIVIER GUAITELLA, ANTOINE ROUSSEAU, *LPP, Ecole Polytechnique, UPMC, Université Paris Sud-11, CNRS, 91128 Palaiseau Cedex, France* The NO formation in low pressure N_2-O_2 plasmas has been studied for a single rectangular pulse using quantum cascade laser (QCL) absorption spectroscopy. To measure sensitive species concentrations with a time resolution in the microsecond range, a new spectroscopic technique based on QCL has been used. Absolute number densities of NO molecules have been obtained taking into account the influence of spectral distortions due to fast spectral scanning, i.e., rapid passage effect. The duration of the pumping pulse was about 5 ms for discharge currents between 50 and 150 mA. The theoretical analysis has been performed by means of a self-consistent model comprising the coupled solution of the time-dependent electron Boltzmann equation, a system of rate equations for various heavy particles and a current balance equation. Results for air-like plasmas are represented both for the active discharge phase and the afterglow. The modelling results show qualitative agreement with experimental data, while the density of NO molecules is underestimated compared to measurements. Possible reasons of this discrepancy are discussed.

PR1 40 Normal regime of dc discharge in N_2O VALERIY LISOVSKIY,* EKATERINA ARTUSHENKO, VLADIMIR YEGORENKOV, *Kharkov National University, Svobody Sq.4, Kharkov 61022, Ukraine* The present report is devoted to studying the normal regime of dc discharge in N_2O with the inter-electrode distance values $L = 0.5$, 1 and 2 cm in a broad range of gas pressure. At large N_2O pressure the ratio of the normal current density to gas pressure squared was shown to remain constant and to equal $J_n/p^2 = 0.44 \pm 0.03$ mA/(cm · Torr)^2 for any inter-electrode distance value (within the L range we studied). On decreasing N_2O pressure the J_n/p^2 ratio grows and for narrow inter-electrode distance it may approach some or even some tens of mA/(cm · Torr)^2. For $L = 2$ cm the normal regime is observed only at the N_2O pressure values above the inflection point on the dc breakdown curve for this inter-electrode distance ($pL \geqslant 0.6$ Torr · cm). But for narrow distance values $L = 0.5$ and 1 cm the normal regime may exist in a much broader N_2O pressure range to the right as well as to the left of the dc breakdown curve minimum. Its existence region is limited from the low pressure side only by the appearance of the obstructed regime at the left-hand branch of the breakdown curve when a complete cathode sheath cannot fit the inter-electrode distance.

*and Scientific Center of Physical Technologies, Svobody Sq.6, Kharkov 61022, Ukraine.

PR1 41 Characteristics of atmospheric pressure microwave plasma torch FERHAT BOZDUMAN, ERDOGAN TEKE, ALI GULEC, LUTFI OKSUZ, *Suleyman Demirel Universitesi* Atmospheric pressure microwave (2.45 GHz) plasma torch has been designed and built. The plasma optical and electrical characteristic have been investigated. The data has been compared with the kHz frequency rf torch. Electron temperature, density and gas temperatures are measured for different flow rates and for different gases. Optical emission spectrometer and ICCD camera are used to measure the argon and helium plasma characteristics and the results are compared for both designs. This Work has been supported by TUBITAK TEYDEB project no: 9100036.

PR1 42 EEDF evolution in pulsed radio-frequency plasmas* ZIAD EL OTELL, MARK BOWDEN, NICHOLAS BRAITHWAITE, *Open University UK* We investigate the evolution of the electron energy distribution function (EEDF) in pulsed radio-frequency plasmas using a simple form of trace rare gas optical emission spectroscopy. For steady-state discharges, methods exist to determine electron temperatures and EEDFs using emission measurements and collisional radiative models. However, these methods rely on the EEDF being stable and are difficult to use in the rapidly changing transients in a pulsed discharge. We assess a simpler technique in which we compare the time-dependence of emission from different plasma species in order to infer information about the evolution of the EEDF. The study was carried out in a capacitively coupled rf discharge generated in a Gaseous Electronic Conference (GEC) reference reactor. The gas mixture consisted of mainly argon with small amounts of xenon and krypton. Emission was measured on specific lines from argon, krypton and xenon, chosen due to their emission being predominantly due to direct excitation from the ground state. For the case of square pulse excitation, the EEDF in the early part of each pulse was dominated by beam-like electrons with high energy. This beam-like EEDF phase was absent when a pulse with a less steep rise time was used.

*Supported by Oxford Instruments Plasma Technology.

PR1 43 Kinetic simulation of the bounce resonance effect in capacitive discharges and beyond* SEBASTIAN WILCZEK, JAN TRIESCHMANN, DENIS EREMIN, RALF PETER BRINKMANN, JULIAN SCHULZE, THOMAS MUSSENBROCK, *Ruhr University Bochum* The electron heating in capacitive high frequency discharges at very low gas pressures is dominated by momentum transfer from the oscillating sheath. In this regime ohmic heating is not sufficient anymore to maintain the plasma. Under certain electric and geometric conditions highly energetic electrons are able to traverse the plasma bulk and interact with the opposite sheath. For proper frequencies and gap sizes the electrons gain energy, accelerate back and resonantly interact with first sheath. The circle may repeat itself. In this contribution the described bounce resonance effect is investigated by means of Particle-In-Cell simulations. It is found that the effect is connected with the excitation of electrostatic waves and the generation of harmonics in the discharge current. It is shown that it is also connected with a very efficient confinement of electrons.

*The authors gratefully acknowledge financial support from the German Research Foundation in the frame of TRR 87.

PR1 44 Numerical investigation on fundamental properties in capacitively-coupled methane plasmas for deposition of diamond-like carbon films* AKINORI ODA, *Department of Electric, Electronics and Information Engineering, Chiba Institute of Technology* HIROYUKI KOUSAKA, *Graduate School of Engineering, Nagoya University* Capacitively-coupled methane (CH_4) plasmas for deposition of diamond-like carbon films have been simulated using a self-consistent one-dimensional fluid model, incorporating the mass balance equations for electrons, ions, radicals and non-radicals, the electron energy balance equation, coupled with the Poisson equation. Despite of low-pressure CH_4 gas condition, many positive-ion species, such as $C_2H_4^+$, CH_4^+, $C_2H_2^+$, CH_5^+ etc., have been found in the plasmas. The non-radical neutrals, such as C_2H_4, C_3H_8, C_2H_2 and C_2H_6, have also found with higher densities comparable to the source gas density. This result indicates that this complexity of background gas in CH_4 plasmas is strongly affected to the electron energy distribution function, which is important for the determination of plasmas properties.

*This work was supported by Grant-in-Aid for Scientific Research (B) of the Japan Society for the Promotion of Science, and Adaptable and Seamless Technology Transfer Program through Target-driven R & D, Japan Science and Technology Agency.

PR1 45 Kinetic simulations of magnetized capacitively coupled discharges* JAN TRIESCHMANN, MOHAMMED SHIHAB, DENIS EREMIN, RALF PETER BRINKMANN, JULIAN SCHULZE, THOMAS MUSSENBROCK, *Ruhr University Bochum* Capacitive high frequency discharges are of crucial importance in the context of plasma etching, deposition and surface modification. As these single or multiple frequency discharges are oftentimes operated at low pressures of less than a few pascal, a high plasma density is commonly achieved with the use of external magnetic fields. In this work kinetic simulations are used to investigate the effect of inhomogeneous external magnetic fields on the discharge dynamics in a strongly nonlocal pressure regime. We found that capacitively coupled discharges can be largely asymmetrized by applying strong magnetic fields in front of a given target electrode. This not only has an effect on the plasma density, but also on the ion energy distribution functions (IEDF) at the electrodes and on the acceleration of fast electrons in the plasma sheath regions. In consequence in the discharge currents a generation of higher harmonics of the driving frequency can be observed. We investigate these scenarios in terms of 1D-3V Particle in Cell simulations.

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

PR1 46 Hydrodynamic modelling of ccrf discharge plasmas in oxygen* MARKUS M. BECKER, IGOR SHEYKIN, DETLEF LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* CHRISTIAN KÜLLIG, KRISTIAN DITTMANN, JÜRGEN MEICHSNER, *Institute of Physics, University of Greifswald, Felix-Hausdorff-Str. 6, 17489 Greifswald, Germany* Capacitively coupled radio frequency (ccrf) oxygen plasmas are widely used for surface treatment applications. In the present contribution hydrodynamic modelling has been performed for discharge plasmas in a reactor with plane parallel electrodes to analyze the impact of negative ions and metastable molecules. Assuming radial symmetry of the plasma a time-dependent, spatially one-dimensional model has been used. The coupled system of Poisson's equation, of balance equations for the densities of 17 heavy particle species and the electrons as well as of the electron energy density has been solved taking into account about 180 collision processes in the reaction kinetics. Main features of the model are given and results for discharges at pressures from 30 to 100 Pa, applied voltages between 0.2 and 1 kV at a frequency of 13.56 MHz are reported. In particular, the electronegativity characteristics and the influence of the secondary electron emission coefficient are discussed. The comparison of modelling results with experimental data of electronegativity and excitation rate of atomic oxygen shows fair agreement.

*The work has been supported by DFG within SFB-TRR 24.

PR1 47 The role of nonlocal electron energy transport in the formation of spatial distributions of the two-chamber plasma density of ICP discharge at change of gas pressure ANATOLY KUDRYAVTSEV, KONSTANTIN SERDITOV, *St. Petersburg State University* 2D simulations of the two-chamber ICP source where power is supplied in the small discharge chamber and extends by electron thermal conductivity mechanism to the big diffusion chamber is performed. Depending on pressure two main scenarios of plasma density and its spatial distribution behavior were identified. The first case of higher pressure is characterized by localization of plasma in small driver chamber where power is deposed and corresponds to small thermal conductivity length compared with diffusion length. The second case of lower pressure represents diffusion chamber as a main source of plasma with maximum of electron density with greater thermal conductivity length compared with diffusion length. The differences in spatial distribution are caused by local or non-local behavior of energy transport in discharge volume due to the different characteristic scale of heat transfer with electronic conductivity. As a result changing of geometrics and gas pressure gives the possibility to set ratio between diffusion and thermal conductivity characteristic lengths. Thus, one can control heat input and, in turn, obtain several types of plasma profiles.

PR1 48 Control of plasma density profile via wireless power transfer in an inductively coupled discharge HEE-JIN LEE, JIN-YOUNG BANG, HYO-CHANG LEE, *Department of Electrical Engineering, Hanyang University* YOUNG-CHEOL KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University* CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Wireless power transfer via a strongly coupled magnetic resonance was applied to the field of plasma. Two antennas (an inner antenna coil was connected to the RF power and an outer antenna was a resonant antenna with a variable capacitor) were placed on the top of a chamber. The resonant antenna is electrically separated from the inner antenna coil. As the self-resonance frequency of the resonant antenna was adjusted, the power transfer ratio of the inner antenna to the outer antenna was changed and a dramatic evolution of the plasma density profile was measured. The density profiles were changed from a concave shape to a convex shape by varying the self-resonance frequency of the outer antenna. This result shows that the plasma density spatial distribution can be successfully controlled via wireless power transfer.

PR1 49 Permanent-magnet helicon discharges at 13 and 27 MHz FRANCIS F. CHEN, *UCLA* A small argon helicon discharge 5 cm in diameter and 5 cm long with a permanent-magnet B-field was studied at 13.56 and 27.12 MHz. RF power varied from 200 to 1000W, and pressures from 0.7 to 60 mTorr. The plasma was injected into a large chamber, and the radial density n and temperature T_e profiles were measured at three distances below the source. The results show the inadequacy of existing theories which assume uniform B-fields and long cylinders. The HELIC code* used for design showed that 27 MHz should give better antenna coupling than 13 MHz, and that the plasma density should increase linearly with power. When the plasma is immediately ejected from the source, however, the density in the source remains relatively low, and the B-field has to be lowered to match it. With optimized B-field, the plasma conditions are quite different from those in ideal theory. The higher densities at 13 MHz are probably due to the fact that the 13-MHz antenna has three turns instead of one, as required to get an inductance that the matching circuit can handle. At 1000W, $n \approx 0.8 \times 10^{12}$ cm^{-3} was achieved 16.9 cm below the source. At 6.8 cm below the source, the Trivelpiece-Gould density peak can be seen at the edge.

*D. Arnush, Phys. Plasmas **7**, 3042 (2000).

PR1 50 Warm Magnetized Primary and Secondary Electron Vlasov Equilibria* ROBERT TERRY, *Enig Associates* A Vlasov equilibrium is developed for steady state emission into a magnetized gap in coaxial geometry. The outer cathode boundary conditions are those of a perfect conductor that emits a Maxwellian electron flux radially, azimuthally, and axially. The interior anode boundary conditions are those of a perfect conductor with a fixed secondary emission coefficient ($0 < \gamma \leqslant 1$). The anode carries a fixed current and the radial gap is set to a fixed voltage. The angular momentum of emitted secondary electrons around the anode is found to materially change the orbit turning points. When energy conserving solutions are examined it is found that the secondaries axial velocities must remain bounded above by a well defined function of radius, magnetic field, and voltage. A fully nonlinear and self consistent Vlasov-Poisson problem is formulated and solved for the space charge distribution implied by the Vlasov equilibrium. The conditions for magnetic insulation of the secondary electron population are then established.

*Work partially supported by DTRA.

PR1 51 Electric Discharges contribute to formation of some Planetary Features* Z. DAHLEN PARKER, *None* From experiments with electric discharges of the surface of a CRT, and through enhancement of energy levels by the placement of objects on that surface, a means for demonstrating the effects of electric discharges to planetary bodies is made available. Estimations of power requirements may be possible through comparison of the electrical dynamics of the CRT screens capacitive surface with the leaky-capacitor characteristics of celestial bodies. The charging of a planetary body seems to be constant but the discharging may take varied forms resultant from terrestrial conditions and from external influences to cause local discharging and broad, hemispheric regional effects, as seen with auroral disturbances. The localized patterns formed can provide clues to the global dynamic. Electric discharge of a surface adjacent to a simulated mountain peak or a ridge line placed on a CRT give specific patterns that are seen at planetary scale. These experiments offer conclusive evidence for the electrical dynamic behind some planetary features.

*Support from The Thunderbolts Project.

PR1 52 Variation of spatial distribution of excited species in He/Ar/O_2 admixtures in an atmospheric pressure plasma jet SARAH TAYLOR, *None* ROBERT LEIWEKE, *Ues, Inc* BISWA GANGULY, *Air Force Research Laboratory* Variation of cathode directed streamer initiated pulsed glow current and spatial distribution of excited species outside the 4 mm capillary of a He/Ar/O_2 plasma jet have been measured using a partially optically transmitting conducting cathode. For 18 mm inter-electrode gap, 15 ns rise time unipolar 12.5 kV pulsed applied voltage with 6 kHz repetition rate, the pulsed glow current peaked at 150 mA with 1% Ar added to He flow, compared to 100 mA in pure He, into ambient air at 1.6 SLM. Spatiotemporally and spectrally resolved head-on emission images from He $3^3D \rightarrow 2^3P$, Ar $2p_1 \rightarrow 1s_2$, O $^5P \rightarrow ^5S$, and N_2^+ $B^2\Sigma \rightarrow X^2\Sigma$ transitions were acquired along the discharge propagation axis using a 5 ns gate ICCD camera. A fiber-couple PMT lens viewing normal to the propagation axis collected the same species emission, at 4 and 8 mm from the capillary tip, in order to correlate temporal emission profiles from streamer to glow transition. For each admixture, the ICCD radial emission profile for each excited species peaks on axis with a mean FWHM of $\sim$1.5 mm, whereas for pure He the intensity distribution of all excited species is annular. Concurrent with the increased discharge conductivity with 1% Ar admixture, the 777 nm O atom emission intensity increased in both streamer and glow phases.

PR1 53 Self-organization, generation, annihilation, and dynamics of filaments in dielectric barrier discharges J.P. BOEUF, B. BERNECKER, T. CALLEGARI, S. BLANCO, R. FOURNIER, *LAPLACE, Universite de Toulouse* The localized objects forming the patterns in Dielectric Barrier Discharges (DBDs) are luminous plasma filaments that exhibit particle-like behaviour, i.e. generation, annihilation, dynamics, scattering, and collective effects leading to self-organized structures (hexagons, stripes, concentric rings, spirals). We use simple experiments and models to study the basic mechanisms behind pattern formation and dynamics in DBDs. Experiments and models show that the formation of filaments can be described in term of activation and inhibition mechanisms, and that the physical quantities playing the role of activators and inhibitors can be clearly identified. We analyze in details the formation of a self-organized pattern after a few cycles of the applied voltage and show how the pattern can evolve on a longer time scale. We also show that the model can reproduce well some aspects of the filament dynamics that are observed in fast imaging experiments, such as division and merging of filaments. The motion of a filament along the dielectric layer can be observed under some conditions and we show that this apparent motion can be the result of an interaction between two filaments, a visible one operating in a glow regime, and a less visible or invisible one operating in a low current, Townsend regime. We discuss how the association of activation-inhibition mechanisms with the important property of bistability of non equilibrium discharges can lead to a large variety of patterns that are very similar to patterns observed in other physical, chemical, or biological systems.

PR1 54 Characterization of three kinds of dielectric barrier discharge reactor for surface treatment of polymers* MIN HUR, WOO SEOK KANG, YOUNG HOON SONG, *Korea Institute of Machinery & Materials* PLASMA ENGINEERING LABORATORY TEAM Low surface energy of polymers is the chief obstacle to prevention of their wider application. It is well known that the exposure of polymers to the plasma leads to the improvement of their printability, dyeability, and adhesion on the one hand by etching their surface on the other hand by grafting functional groups on their surface. In this work, three kinds of dielectric barrier discharge (DBD) reactor are proposed for surface treatment of polymer substrates. The discharge characteristics are investigated by using the voltage-current waveforms and optical emission spectroscopy. The plasma-modified polymer surfaces are characterized with contact angle measurement, scanning electron microscope, and x-ray photoelectron spectroscopy. Finally, the applicability of three kinds of DBD reactors to the polymer surface treatment is discussed based on the experimental results.

*This work is supported by the Basic Research Program of the Korea Institute of Machinery & Materials.

PR1 55 Characteristics of low frequency air glow dielectric barrier discharges at atmospheric pressure* NAKYUNG HWANG, SEONG-KYUN IM, MOON SOO BAK, MARK A. CAPPELLI, *Stanford University* In this paper we present recent studies of dielectric barriers discharges in air. The discharges are generated using an AC power supply operating at a relatively low frequency of 60 Hz between two sheets of porous dielectric material of varying thickness measuring 20 mm $\times$ 20 mm in area. Measurements are made of the optical emission and voltage–current waveforms from which we extract discharge properties including electron density, under different input voltage, electrode separation, and dielectric thickness. Stable and continuous air glow discharges were obtained at atmospheric pressure in the range of 2–5 kV and current densities of a few mA for 0.5–2.5 mm discharge gaps. Regions of stable glow discharges are mapped out and a plausible mechanism is described for the transition from glow to streamer mode. The experimental results are compared to one-dimensional numerical simulations that are carried out for a discharge pressure range of 100–760 Torr.

*This research is supported by the National Science Foundation, and by University of Science and Technology.

PR1 56 Electric arc discharge in the transverse gas flow at atmospheric pressure VALERIY CHERNYAK, IRYNA PRYSIAZHNEVYCH, EVGEN MARTYSH, TAMARA LISITCHENKO, *Kyiv National Taras Shevchenko University* KYIV NATIONAL TARAS SHEVCHENKO UNIVERSITY TEAM Physical features of the transverse arc discharge (TA) and its atmospheric pressure plasma were investigated for the wide range of gas flow rates (0 ÷ 3/4 of the sound speed) and for the different gas content (atomic - Ar, molecular - air) and different character of gas flows (from laminar to turbulent). Component composition of the plasmaforming gas; electronic excitation temperatures T_e^* of atoms, vibration T_v^* and rotation T_r^* temperatures of molecules in the generated plasma were determined by optical emission spectroscopy. The electron distribution function and its average energy were calculated by using Bolsigplus code. The difference between T_e^* of electrode material atoms (cooper) and atoms of blowing gas (oxygen, hydrogen, argon) was found. It can be explained by the additional mechanism of the population of electronic states of cooper atoms due to the ion-ion recombination. It was shown that when the gas flow rate achieves values larger than the drift velocity of ions in an electric field of the discharge further increasing of the voltage drop on the discharge starts with the gas flow rate growth, which is accompanied by appearance of numerous filament structures oriented along the gas flow.

PR1 57 Modeling of the DBD in Xe-Cl_2 mixtures: effect of chlorine concentration and pressure SVETLANA AVTAEVA,* *Kyrgyz-Russian Slavic University, Bishkek, Kyrgyzstan* BELKACEM SAGHI,† BOUABDELLAH RAHMANI, *Mohamed Boudiaf University of Science and Technology, Oran, Algeria* Characteristics of the DBD in Xe-Cl_2 mixtures were simulated using the 1D fluid model at gas pressure 150-300 Tor and chlorine concentration in the mixtures 0.1–5%. The discharge gap is fixed at 4 mm. Two dielectric layers have an identical thickness 2 mm and relative permittivity 4. The source voltage $U_S = U_0\ sin\omega t$ with $f =$ 100 kHz and $U_0 = 4.25$ or 5 kV is applied to the electrodes. Simulations show at all chlorine concentrations in the Xe-Cl_2 mixtures the most abundant negative species in the discharge are Cl^- ions, the most abundant positive ions are Xe_2^+. At the current pulse densities of electrons and Xe^+ ions near the dielectric barrier sharply increases. The potential drop across the discharge gap increases and the magnitude of the current pulse falls with chlorine content in the mixture. Power deposited into heating of positive and negative ions grows with chlorine concentration; power deposited into electrons mainly decreases with chlorine concentration. Growth of the chlorine content in Xe-Cl_2 mixtures results in increase of electron energy expenses on Cl_2 dissociation, Xe and Cl_2 ionization, and Cl_2^* and Xe^{**} excitation. At chlorine concentration higher than 0.1% emission of the $XeCl^*$ 308 nm band predominates in radiation flux. The DBD radiative efficiency decreases with pressure and has maximum at small chlorine concentration.

*Department of Physics and Microelectronics.
†Department of Electronics.

PR1 58 Fully kinetic particle simulations of high pressure streamer propagation* DAVID ROSE, DALE WELCH, CARSTEN THOMA, ROBERT CLARK, *Voss Scientific* Streamer and leader formation in high pressure devices is a dynamic process involving a hierarchy of physical phenomena. These include elastic and inelastic particle collisions in the gas, radiation generation, transport and absorption, and electrode interactions. We have performed 2D and 3D fully EM implicit particle-in-cell simulation model of gas breakdown leading to streamer formation under DC and RF fields. The model uses a Monte Carlo treatment for all particle interactions and includes discrete photon generation, transport, and absorption for ultra-violet and soft x-ray radiation. Central to the realization of this fully kinetic particle treatment is an algorithm [D. R. Welch *et al.*, J. Comp. Phys. **227**, 143 (2007)] that manages the total particle count by species while preserving the local momentum distribution functions and conserving charge. These models are being applied to the analysis of high-pressure gas switches [D. V. Rose *et al.*, Phys. Plasmas **18**, 093501 (2011)] and gas-filled RF accelerator cavities [D. V. Rose *et al.*, Proc. IPAC12, to appear].

*Funded by the US Department of Energy.

PR1 59 Experimental study of pulsed corona discharge in air at high pressures YUNGHSU LIN, DAN SINGLETON, JASON SANDERS, ANDRAS KUTHI, MARTIN A. GUNDERSEN, *University of Southern California* Understanding of the dynamics of nanosecond scale pulse discharges in air at multiatmospheric pressure is essential for the development of transient plasma enhanced combustion in internal combustion engines. Here we report the result of our experimental investigation of cathode-directed streamer discharges in synthetic air at pressures ranging from 1 to 20 bar. Two pulse generators with maximum pulse amplitudes of 50 kV and 65 kV, pulse width of approximately 12 ns and 85 ns and pulse rise times of 5 ns and 50 ns are used to generate streamers. The electrodes are coaxial with various radial gaps up to 11.75 mm. The discharge chamber is evacuated and backfilled with synthetic dry air at room temperature. Optical data is obtained from PI-MAX 3 ICCD camera with 3 ns gate width. The streamer propagation velocity variation with applied voltage, different pressures and reduced electric field, E/P, will be shown. Preliminary results indicate that the (pd) similarity law is violated at high pressures in agreement with other recent experiments [1].

[1]"Nanosecond Scale Discharge Dynamics in High Pressure Air," Pierre Tardiveau, Nicolas Moreau, François Jorand, Christian Postel, Stéphane Pasquiers, and Pierre Vervisch, IEEE Trans. on Plasma Sci., Vol. 36, No. 4, 2008.

PR1 60 Estimates of the Electric Field in Fast Ionization Waves BENJAMIN YEE, *University of Michigan* BRANDON WEATHERFORD, EDWARD BARNAT, *Sandia National Laboratories* JOHN FOSTER, *University of Michigan* The non-equilibrium nature of fast ionization waves (FIWs) makes an assessment of energy transport difficult. Their high fields and short-lived nature complicate even the most simple diagnostics and tends to preclude the application of any physical probe. On the other hand, optical probes generally require the excitation, equilibration, and decay of atomic or molecular states, each of which takes a finite amount of time. In the case of an FIW, measurement of optical transitions will necessarily take place in the afterglow of the plasma. Fortunately, the electron and excited state densities produced by the wavefront are essentially fixed for a few hundred nanoseconds after the pulse. We propose a technique which uses measurements of the absolute metastable and electron densities to determine an effective electric field in the wavefront. The approach is evaluated for self-consistency and is in compared with other estimates of the electric field in similar discharges.

PR1 61 Influence of electrode positions and gas flow on the onset and propagation of an atmospheric pressure plasma jet CLAIRE DOUAT, GERARD BAUVILLE, MICHEL FLEURY, VINCENT PUECH, *Laboratoire de Physique des Gaz et des* *plasmas - CNRS and Univ. Paris Sud, Orsay, France* Plasma jets produced in noble gases by pulsed discharges and propagating in surrounding air have recently attracted a lot of attention due to their physical properties enabling the development of new applications, such as plasma medicine. Our device consisted of a quartz tube with inner and outer diameters equal to 2mm and 4mm, respectively. Helium was flowing through the inner electrode connected to a pulsed high voltage, while a grounded copper electrode was wrapped around the tube. Helium flow was in the range from 1 to 6 slm. The plasma jet propagated inside grounded metallic tubes of different diameters, allowed to study the influence of the location of the external potential on the propagation of the plasma. It will be shown that the discharge breakdown voltage, the onset of a plasma jet, its length of propagation and the velocity of the ionization front are sensitive function of the electrode arrangement, of the location of the reference potential and of the gas flow. All these parameters interplayed in a complex manner. It will be shown how minor changes in the overall configuration can induce dramatic effects on the properties of the plasma jet.

PR1 62 Experimental studies and modeling of microwave plasmas in argon M. ANDRASCH, M. BAEVA, J. EHLBECK, D. LOFFHAGEN, K.-D. WELTMANN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* A microwave (MW) induced plasma in argon at pressures from 5 to 100 hPa has been studied by experiments and modeling. The plasma source is placed inside a vacuum vessel and is operated with a TEM supply at a field frequency of 2.45 GHz provided by a 2 kW magnetron. To provoke the discharge, a resonant structure has been used which is integrated at the end of the inner conductor. The gas flow rate is 30 to 1000 sccm and the absorbed power derived from the incoming and reflected power is between 20 and 125 W. The temporally resolved electron density in the plasma afterglow has been determined by a heterodyne MW interferometer working at 45.5 GHz. In addition, a two-dimensional fluid model describing in a self-consistent manner the gas flow and heat transfer, the energy in-coupling, and the reaction kinetics has been utilized to obtain the gas and electron temperature, the electron, ion, and excited state densities, and the power deposited into the plasma for given gas flow rate and temperature at the inlet and input power of the incoming TEM microwave. A maximum electron density above 1×10^{20} m^{-3} and gas temperature above 600 K have been determined in front of the resonant structure. Modeling and experimental results demonstrate good agreement.

PR1 63 Generation of Energetic Species by RF Microplasma Arrays* W.T. RAWLINS, S. LEE, D.B. FENNER, S.J. DAVIS, *Physical Sciences Inc., Andover MA* A.R. HOSKINSON, J. HOPWOOD, *Electrical and Computer Engineering, Tufts University, Medford MA* We present preliminary results from the first implementation of a prototype single-board RF micro-discharge, linear array device in a discharge-flow reactor for quantitative determinations of ozone and singlet-oxygen production from microplasmas in O_2 and air at 1 atm. The ultimate objective is to develop compact, portable low-power micro-discharge based systems to generate energetic species for atmospheric-pressure applications including decontamination and disinfection. The technology uses application of low DC voltages and low applied powers (~25 W) at ~1 GHz frequencies, across small gaps in arrays of resonators to ignite and sustain highly energetic microplasmas at elevated pressures. A set of 15-resonator micro-discharge assemblies was designed, fabricated, and tested in static and flowing environments for O_2, air, and Ar flows at pressures of 20 Torr to 1 atm. O_3 production was measured by UV absorption spectrometry, and $O_2(a^1\text{delta}_g)$ ("singlet-oxygen") concentrations were determined by absolute near-infrared emission spectroscopy. Near-infrared emission spectra from an argon plasma were also recorded, and showed extensive excitation of the Ar(I) $3p^54p - 3p^54s$ emission system near 12 eV.

*Supported by Air Force Research Laboratory and Department of Energy.

PR1 64 Radial profile of micro-discharge temperature measured by ultraviolet laser Rayleigh scattering* STEVEN ADAMS, *Air Force Research Laboratory* JAMES CAPLINGER, *Wright State University* Air micro-discharge temperature profiles have been derived from measurements of elastic Rayleigh scatter of an ultraviolet laser pulse. Rayleigh scatter images have been recorded to measure spatially resolved translational temperatures along the radial dimension of the dc micro-discharge at various currents. The scatter image intensity along the laser beam axis is proportional to the background gas target density and thus, according to the ideal gas law, is inversely proportional to gas translational temperature. By measuring the scatter image with and without a discharge, the temperature was determined in one-dimension along the laser beam passing radially through the discharge. This laser scatter technique was compared to the technique of measuring rotational and vibrational temperatures by passive optical emission spectroscopy (OES) of the N_2 second positive system. Results were generally consistent with the common assumption that $T_{vibrational} \gg T_{rotational} = T_{translational}$. Slight differences between $T_{rotational}$ and $T_{translational}$ measured by laser scatter and OES techniques respectively are discussed.

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

PR1 65 Surface-wave capillary plasmas in helium: modeling and experiment* M. SANTOS, L.L. ALVES, *IPFN/IST-UTL, Portugal* C. NOEL, T. BELMONTE, *LSGS/CNRS, France* In this paper we use both simulations and experiments to study helium discharges (99.999% purity) sustained by surface-waves (2.45 GHz frequency), in capillary tubes (3 mm radius) at atmospheric pressure. Simulations use a self-consistent homogeneous and stationary collisional-radiative model that solves the rate balance equations for the different species present in the plasma (electrons, the He^+ and He_2^+ ions, the He(n<7) excited states and the He_2* excimers) and the gas thermal balance equation, coupled to the two-term electron Boltzmann equation (including direct and stepwise collisions as well as electron-electron collisions). Experiments use optical emission spectroscopy diagnostics to measure the electron density (H_β Stark broadening), the gas temperature (ro-vibrational transitions of OH, present at trace concentrations), and the populations of different excited states. Model predictions at $1.7\text{x}10^{13}$ cm^{-3} electron density (within the range estimated experimentally) are in good agreement with measurements (deviations <10%) of (i) the excitation spectrum and the excitation temperatures (2795 ± 115 K, obtained from the Boltzmann-plot of the excited state populations, with energies lying between 22.7 and 24.2 eV), (ii) the power coupled to the plasma (~180 ± 10 W), and (iii) the gas temperature (~1700 ± 100 K). We discuss the extreme dependence of model results (particularly the gas temperature) on the power coupled to the plasma.

*Work partially supported by FCT (Pest-OE/SADG/LA0010/2011).

PR1 66 Diamond-based microdischarges: the effect of high thermal conductivity on plasma properties* SEBASTIEN MITEA, MARK BOWDEN, NICHOLAS BRAITHWAITE, *Open University UK* MONIKA ZELEZNIK, PAUL MAY, NEIL FOX, JUDY HART, *University of Bristol UK* CHANTAL FOWLER, ROBERT STEVENS, *Rutherford Appleton Laboratory UK* Diamond is a promising substrate material for microdischarges, due to its high thermal conductivity, low sputter yield, high secondary electron emission and compatibility with microelectronics fabrication processes. We have recently demonstrated that microhollow cathode discharges can be fabricated in an all-diamond structure, with diamond being used as the insulating material and boron-doped diamond thin films being used as the electrode material [S. Mitea *et al.*, Plasma Sources Sci. Technol. 21, 022001 (2012)]. In this study, we report on the effect of diamond's high thermal conductivity on device behaviour. The gas temperature during plasma operation was determined by measuring emission from nitrogen molecules present in trace amounts in the discharge gas, and calculating the rotational temperature from emission from the nitrogen 2nd positive system. Results for diamond were compared with similar devices in other substrates in order to determine the role of the material on microplasma operation. Preliminary results indicate that gas temperature is significantly lower in the diamond-based devices.

*funded by the UK Engineering and Physical Sciences Research Council.

PR1 67 Kinetic simulations of artificial plasma material structures* JAN TRIESCHMANN, THOMAS MUSSENBROCK, *Institute for Theoretical Electrical Engineering, Ruhr-University Bochum* Artificially structured materials with underlying spatial periodicity (photonic crystals) are known for their unique electromagnetic properties. These materials allow to restrict propagation of electromagnetic waves within certain frequency ranges, in particular in the microwave regime. Electromagnetic bandgaps as well as complex waveguide structures can be achieved. In this contribution we study the influence of microplasmas on the electromagnetic behavior of these metamaterials. We show that the electromagnetic wave propagation can be completely suppressed by activating the microplasmas. In order to understand the interaction in detail, we investigate the electromagnetic response of a bulk plasma as well as a one-dimensional array of plasmaslabs by means of self-consistent kinetic simulations. Hereby we find that fully plasma based photonic crystals indeed can be achieved, enabling for the unique switchable manipulation of electromagnetic waves in the microwave regime.

*This work is supported by the German Research Foundation within the frame of the FOR 1123.

PR1 68 Ionization coefficient measurements in DC microplasmas* ILIJA STEFANOVIC, *Experimental Phys. II, Ruhr Universitaet, Bochum, Germany* THOMAS KUSCHEL, JOERG WINTER, *Experimental Phys. II, Ruhr Universitaet* DRAGANA MARIC, *Institute of Physics, University of Belgrade, Serbia* ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade* EXP. PHYS. II BOCHUM TEAM, GASEOUS ELECT. BELGRADE TEAM While steady state Townsend discharges may provide data for ionization coefficients those are often not as accurate as those produced in dedicated pulsed current growth experiments. In this paper we show that one may be able to measure ionization coefficients in DC microdischarges that are of excellent quality. Measurements were made for argon and argon/nitrogen mixtures with different gas flow rates. The technique based measuring the spatial profile of emission a Townsend discharge. In spite of having the drift length of only 1 mm, excellent agreement has been found between our new measurements and the data for low-pressure, larger dimension (2–4 cm) discharges in argon (Jelenak *et al.*) for the E/N in the range from 300 Td to 4000 Td, where E/N is normalized electrical field strength. Below 300 Td our measured values are larger then those by Jelenak *et al.* This discrepancy with previous measurements will be discussed. The influence of the gas flow-rate and nitrogen concentration on the radial discharge profile in the Townsend mode will also be presented and discussed.

*DFG FOR1123 and MNTRS Proj. 171037 and 41011.

[1]Jelenak *et al.*, Phys. Rev. E **47**, 3566 (1993).

PR1 69 Investigating voltage recovery after breakdown supercritical nitrogen* ARAM MARKOSYAN, *Centrum Wiskunde and Informatica, Amsterdam* JIN ZHANG, BERT VAN HEESCH, *Eindhoven University of Technology* UTE EBERT, *Centrum Wiskunde and Informatica, Amsterdam* We simulate the thermal shock and induced pressure waves caused by electrical breakdown of supercritical nitrogen. The goal is to investigate the temperature evolution after breakdown, thus predicting the recovery rate of a plasma switch based on supercritical liquids. The system of fluid equations is used to obtain the spatial and temporal evolution of liquid density, pressure, velocity and energy. We compare simulation and experimental results.

*Work supported by STW-project 10751.

PR1 70 Influence of gas composition on characteristics of self-organized pattern formation observed in atmospheric DC glow discharge using liquid anode* NAOKI SHIRAI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* TOKYO METROPOLOTAN UNIVERSITY TEAM Non-thermal plasma in and with liquids has attracted considerable interest for its potential use in a wide range of applications. In particular, the use of a discharge with a liquid as an electrode for analytical techniques and material processes has been reported. Previously, we investigate fundamental characteristics of atmospheric dc glow discharge using liquid electrode with miniature helium flow. Especially, when liquid anode discharge is generated, self-organized luminous patterns are observed on the liquid surface at a creation condition. Although the mechanisms of this pattern formation have not understood completely, we assume that the patterns are dependence on negative ion in the discharge from previous results. In this study, we feed oxygen gas flow to atmospheric dc discharge using liquid anode in order to investigate the influence of negative ion on the condition of self-organized pattern formation. When oxygen gas flow is fed to the discharge space, anode luminous patterns are changed from ring patterns to several dots patterns. Therefore the pattern formation may depend on the negative ion in the discharge. It presumes that a certain reaction such as generation and quenching of electron has occurred on the anode surface.

*This work was supported financially in part by a Grant-in-Aid for Scientific Research on Innovative Areas (No 21110007).

PR1 71 Atmospheric negative corona discharge using a Taylor cone as liquid electrode* RYUTO SEKINE, NAOKI SHIRAI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* TOKYO METROPOLITAN UNIVER-

SITY TEAM We examined characteristics of atmospheric negative corona discharge using liquid needle cathode. As a liquid needle cathode, we adopted Taylor cone with conical shape. A nozzle with inner diameter of 10 mm is filled with liquid, and a plate electrode is placed at 10 mm above the nozzle. By applying a dc voltage between electrodes, Taylor cone is formed. To change the liquid property, we added sodium dodecyl sulfate to reduce the surface tension, sodium sulfate to increase the conductivity, and polyvinyl alcohol to increase the viscosity, in distilled water. The liquid, with high surface tension such as pure water could not form a Taylor cone. When we reduced surface tension, a Taylor cone was formed and the stable corona discharge was observed at the tip of the cone. When we increased viscosity, a liquid filament protruded from the solution surface was formed and corona discharge was observed along the filament at position 0.7-1.0 mm above from the tip of the cone. Increasing the conductivity resulted in the higher light intensity of corona and the lower corona onset voltage. When we use the metal needle electrode, the corona discharge depends on the voltage and the gap length. Using Taylor cone, different types of discharges were observed by changing the property of the liquid.

*This work was partly supported financially by a Grant-in-Aid for Young Scientists (B)(No. 23740409).

PR1 72 Plasma-Generated Reactive Species in physiological Solutions* MALTE U. HAMMER, HELENA TRESP, ANSGAR SCHMIDT-BLEKER, JÖRN WINTER, *ZIK plasmatis at the INP Greifswald e.V.* KLAUS-DIETER WELTMANN, *INP Greifswald e.V.* STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* Plasma-generated reactive species, like ROS and RNS, in liquids are essential for plasma medicine caused by their role in mammalian systems. Especially free radicals and nitric monoxide are important. Here the focus is set on plasma-generated reactive species in physiological solutions such as cell culture medium, sodium chloride solution, and phosphate buffered saline. The detection of free radicals was performed via electron paramagnetic resonance (EPR) spectroscopy. Additionally electro chemical detection for pH value and concentration of H_2O_2 was realized in parallel to each experiment. Because nitric oxide is rapidly oxidized to nitrate and/or nitrite by oxygen, the measurement of nitrate and nitrite concentration as the end products of NO hold as an index for the integrated nitric oxide production. Nitrite and nitrate play a key role in plasma-treated liquids. For this work a colorimetric assay was used for nitrate and nitrite concentrations measurements. The control of species, which can diffuse into the effluent of an atmospheric pressure plasma jet, is necessary. A gas curtain was build and its effect on reactive species production in liquids was investigated. The gas curtain was used with varying ratios of nitrogen and oxygen as shielding gas.

*This work is founded by German Federal Ministry of Education an Research (grant # 03Z2DN12).

PR1 73 Optical Emission Studies of Micro-Plasma Balls Formed from Laser Induced Breakdown in Water L. HUWEL, O. FINARD, R. HAYDAR, E.B. JONES, T.J. MORGAN, *Wesleyan University* W. GRAHAM, *Queens University Belfast* We present experimental results on the optical emission resulting from nanosecond pulse laser induced breakdown in distilled water. A Q-switched 1064 nm wavelength Nd:YAG laser is focused into a water cell and light is observed at 90 degrees to the laser beam propagation axis using two synchronized intensified-CCD cameras and a spectrometer. Both temporal and spatial emission dependence have been recorded. Signal is observed up to 500 ns after ignition. The spatial extent of the emission is about 3.5 mm and the center-of-emission intensity propagates away from the laser with delay time. The emission data reveal a disconnected string of micro-plasma balls along the laser propagation axis of size tens of microns resulting from a single laser shot, and correlated in time and space. Detailed analysis of the structure and time evolution of the data will be presented at the conference including spectroscopic results.

PR1 74 Plasma formation inside deformed gas bubbles submerged in water* BRADLEY SOMMERS, JOHN FOSTER, *University of Michigan* Plasma formation in liquids produces highly reactive products that may be desirable for a variety of applications, including water purification and waste processing. The direct ignition of plasma in these environments, however, is limited by the large breakdown strength of liquids, which imposes severe voltage and energy requirements on the design of practical devices. One way to address this issue is by first igniting plasma in gas bubbles injected into the water. These bubbles provide an environment with higher reduced electric field (E/N) that is more suitable for plasma formation. If the same bubbles can be excited into strong distortions of their shape and volume, then it is possible to further alter E/N, both by field enhancement at the bubble's highly distorted dielectric interface (via E) and by fluctuations in its internal gas pressure (via N). This principle is investigated by trapping a single bubble at the node of a 26.4 kHz underwater acoustic field and driving it into violent oscillations using an A.C electric field. A third high voltage needle is placed nearby and used to ignite plasma in the bubble at various points during its oscillation. The bubble response is captured using a high speed camera capable of up to 30,000 frames per second.

*Research supported by the NSF (CBET #1033141).

PR1 75 Time Resolved Spectroscopy: Dynamic Study of a Dielectric Barrier Discharge Plasma* SARAH GUCKER, *University of Michigan - Ann Arbor* MARIA GARCÍA, *Universidad de Córdoba, Spain* BENJAMIN YEE, JOHN FOSTER, *University of Michigan - Ann Arbor* Atmospheric pressure plasmas have prompted strong interest due to their potential application to a wide range of fields and technologies (such as materials processing and medical applications). When these atmospheric discharges are created within a gas bubble and liquid water medium, vast quantities of short-lived, highly oxidative particles are produced. These plasmas have been shown to possess the capacity to decompose aromatic compounds and other contaminants, thereby leading to the sterilization of the water. Here, the results from a dielectric barrier discharge plasma jet in liquid water operating on a variety of gases are presented. These plasmas display several distinct physical characteristic over a power cycle; therefore, the chemical dynamics taking place in the liquid is also expected to have a similar time dependence. Non-evasive, dynamic methods are necessary to probe these dynamic systems. Presented here are time-resolved optical emission spectroscopy measurements aimed at quantifying the fundamental characteristics of the plasma such as temperature and density- and how they evolve throughout the discharge cycle.

*This material is based upon work supported by the National Science Foundation (CBET 1033141) and the National Science Foundation Graduate Student Research Fellowship under Grant No. DGE 0718128.

PR1 76 Ambipolar diffusion in strongly electronegative plasma VALERIY LISOVSKIY,* VLADIMIR YEGORENKOV, *Kharkov National University, Svobody Sq.4, Kharkov 61022, Ukraine* This paper presents the treatment of the analytical model of ambipolar diffusion in quasi-neutral electronegative plasma consisting of electrons, a single species of negative ions and a single species of positive ions, which was proposed by Thompson J. B. [Proc. Phys. Soc., 73 (1959) 818]. We demonstrate that in plasma with the concentration of negative ions more than 10 times exceeding that of electrons one has to take into account the mobility of negative and positive ions. We established that in strongly electronegative plasma when both conditions $\alpha \gg 1$ ($\alpha = n_-/n_e$) and $\mu_e \ll \alpha \cdot \mu_-$ hold, the ambipolar diffusion coefficients for positive and negative ions as well as electrons are close to the coefficients of their free diffusion. Consequently in strongly electronegative plasma the diffusion ceases to be ambipolar (even for large plasma concentration) and becomes to be free, i.e. charged particles of different species and sign cease to affect the diffusion motion of each other.

*and Scientific Center of Physical Technologies, Svobody Sq.6, Kharkov 61022, Ukraine.

PR1 77 Study of dust particle charge screening within the nonlocal charging theory NATALIA DEMKINA, IVAN DERBENEV, ANATOLY FILIPPOV, *Troitsk Institute for Innovation and Fusion Research* In papers [1,2] it was shown that in a non-equilibrium plasma with one type of positive ions the dust particle potential was described by two exponentials, and for the case of three types of ions the potential was described by the superposition of three exponentials with three different screening constants [3]. In the present paper the EEDF non-locality influence on a dust particle potential distribution is considered in a two-component plasma of noble gases and nitrogen on the basis of a nonlocal charging model which consists of the electron and ion balance equations, the Poisson equation and the electron energy balance equation, obtained from the non-local momentum method [4]. It was found that the potential distribution in the vicinity of a dust particle is described by the sum of three exponentials. The screening constants and the pre-exponential coefficients are defined by the plasma parameters and the electron and ion sinks.

[1]A. V. Filippov *et al.*, JETP Letters **81**, 146 (2005).
[2]A. V. Filippov *et al.*, JETP **104**, 147 (2007).
[3]I. N. Derbenev and A. V. Filippov, Plasma Phys. Rep. **36**, 105 (2010).
[4]A. V. Filippov *et al.*, Plasma Phys. Rep. **29**, 190 (2003).

PR1 78 Anomalous electron density behaviour in dusty plasma afterglow* IRINA SCHWEIGERT, ANDREY ALEXANDROV, *Institute of Theoretical and Applied Mechanics SB RAS* The anomalous increasing of electron density in RF discharge plasma with strong dust contamination after discharge switching-off was observed in experiment (J. Berndt *et al.*, Plasma Sources Sci. Technol., 2006, **15**, 18). A possible mechanism of this is the discharging of negatively charged dust particles in afterglow plasma. The existing theoretical models of dust discharging due to ion flux show that it is not efficient to provide the observed electron density growth. In this work, it is assumed that the more fast mechanism of dust discharging is electrons desorption from dust surface. The afterglow of heavy dusted plasma in argon was simulated by PIC-MCC method, including electrons desorption from dust and metastable argon atoms kinetics. The analysis of the electron energy distribution function shows, that the fast electrons rapidly depart from the plasma volume, thus leading to dust surface potential magnitude and hence the dust charge drop. As a result, the electrons are released from dust particles, providing the anomalous electron density increasing. The metastable pooling ionization enlarges the electron density and temperature, but cannot provide the anomalous peak of electron density.

*This work was supported by Siberian Branch of RAS Integration project No. 39-2012.

PR1 79 Electrical asymmetry effect for controlling the transport of micrometer-sized particles in capacitively coupled plasmas SHINYA IWASHITA, EDMUND SCHUENGEL, JULIAN SCHULZE, *Ruhr University Bochum* GIICHIRO UCHIDA, KAZUNORI KOGA, *Kyushu University* PETER HARTMANN, *Wigner Research Centre for Physics, Hungarian Academy of Sciences* MASAHARU SHIRATANI, *Kyushu University* ZOLTAN DONKO, *Wigner Research Centre for Physics, Hungarian Academy of Sciences* UWE CZARNETZKI, *Ruhr University Bochum* We have developed a novel method to control the dust particle transport in capacitively coupled plasmas via the electrical asymmetry effect (EAE) [1]. At low pressures the EAE allows controlling the spatial potential profile and the ion density distribution by adjusting the phase angle between a fundamental frequency and its second harmonic, resulting in control of forces exerted on dust particles such as electrostatic and ion drag forces. We report the experimental results of this method using SiO_2 particles of 1.5 μm in size, which are inserted into an argon discharge. Initially dust particles tend to be confined at the sheath edge near the bottom electrode, and the change of their equilibrium position with plasma due to the adiabatic phase shift can be well understood by the electric field profile obtained from a simple analytical model. By applying the abrupt change of phase angle from 90° to 0° dust particles are transported between both sheaths through the plasma bulk [1]. Based on the model of this transport [1] the potential profile can be obtained by experimental results.

[1]Iwashita S *et al.*, Plasma Sources Sci. Technol. **21**, 032001 (2012).

PR1 80 The technique to measure the internal temperature of particulates/droplets: Two-color laser induced fluorescence* DAISUKE OGAWA, LAWRENCE OVERZET, MATTHEW GOECKNER, *The University of Texas at Dallas* In a multi-phase plasma (such as dusty plasma and plasma spray etc.), it is important to know the internal temperature of particulates. This is because the temperature affects chemical properties of the particulates. For example, it affects the chemical reaction rate, the material state, the vapor flux etc. Among some techniques to measure the temperature, we selected the technique called two-color laser induced fluorescence (2cLIF) in order to find the droplet temperature in argon plasma. In fact, the use of two wavelengths for the particulate pyrometery is known. This technique uses the ratio of two fluorescent intensities which emit from dye (rhodamine b) in the droplets. The ratio cancels out some unknown parameters (optical constants, incident intensity etc.) and depends on the particulate temperature. Our preliminary measurements showed that the ratio of the intensity at 580 to 605 nm monotonically decreased as the liquid temperature increased. Currently, we found the temperature decreased approximately 40 to 70 degrees C at low pressure (100 mTorr, no plasma) compared to droplets injected to atmospheric pressure. In our poster, the theory behind the technique and the actual measurements with the technique will be shown.

*This material is based upon work supported by the Department of Energy under award number DE-SC0001355.

PR1 81 Hole current confinement effects in elliptic tokamak plasmas with triangularity* PABLO MARTIN, ENRIQUE CASTRO, JULIO PUERTA, *Universidad Simon Bolivar* The effect of hole currents in tokamak plasma confinement is analyzed here. Banana width and inward pinch due to toroidal electric field are considered for tokamak plasmas with the same ellipticity and triangularity but with or without hole currents. The banana width increases with the banana amplitude for plasmas with no-hole current, however, with hole current the maximum width happens for intermediate amplitudes. The plasma ellipticity and triangularity influences also the results, which will be shown analytic and graphically. All our calculations show that in the limit of large aspect ratio with circular plasmas shape the well known Ware Pinch is recovered. Positive triangularity will be only considered in this work. The analyses were carried out using the profiles of the toroidal density current in JT-60U and JET.

*Supported by DID-G22 Universidad Simon Bolivar.

PR1 82 Secondary Electron Yield from Plasma-Treated Niobium MILOS BASOVIC, RAJINTHA TISKUMARA, ANA SAMOLOV, FILIP CUCKOV, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Center for Accelerator Science, Old Dominion University* Future room-size linear accelerators, incorporated in compact light sources and medical therapeutic systems, will use Superconducting Radio Frequency (SRF) cavities to achieve the required beam energy over limited distances. The inhibiting phenomena in these designs are among others resonant multipactor discharges. Present study is intended to help complex cavity surface modification leading to mitigation of multipactors. Behavior of the multipactor discharges depends on the microwave field configuration and on the Secondary Electron Yield (SEY) from the cavity surface. Contaminated surfaces show substantial increase of SEY. Our aim is to reduce SEY using *in-situ* surface treatment with microwave discharge. We have developed an experimental set up to study the effect of plasma surface treatment on SEY. The system is designed to measure energy distribution of SEY on coin like samples under different incident angles. Clean, contaminated, and plasma-treated samples are placed in a carousel target manifold. Samples and the manifold are manipulated by robotic arm providing multiple degrees of freedom of a whole target system. Here we are reporting our progress and preliminary results from testing the Nb surface samples.

PR1 83 Rotating arc plasma characteristics in the presence of methane flame NAKYUNG HWANG, *Stanford University* DAE HOON LEE, KWAN TAE KIM, YOUNG-HOON SONG, *Korea Institute of Machinery and Materials* Plasmas can ignite and stabilize flames under extreme conditions and have already been applied in practical combustors, but further studies are needed to elucidate the complex flame–plasma interactions. Here, we present the results of an experimental study on the interactions between a methane flame on a rotating arc plasma, with particular focus on the influence of flame conditions on plasma generation. A gas chromatograph, chemiluminescent NO_x analyzer, optical emission spectrograph, and intensified charge-coupled device were used to monitor product gases (CO_2, H_2, CO, C_2, C_3, and NO_x) with and without the plasma and also plasma characteristics (arc length, angular speed, and peak voltage) under different flame equivalence ratios Φ. The results confirmed that the rotating arc indeed stabilized the flame and extended both flammability limits. In addition, the rotating arc was pushed upward and out of the reactor for rich and lean mixtures. The highest NO_x concentration was obtained at the lower flammability limit in the presence of the plasma, but at $\Phi = 1.0$ without the plasma.

PR1 84 Current Distribution Characterization and Circuit Analysis of a High Energy Pulsed Plasma Deflagration KEITH LOEBNER, FLAVIO POEHLMANN, MARK CAPPELLI, *Stanford University* Measurements and analysis of the transient current density within a coaxial electromagnetic plasma accelerator operating in a pulsed deflagration mode are presented. Current measurements are performed using an axial array of dual-Rogowksi coils in a balanced circuit configuration. An equivalent circuit model of the accelerator is formulated and compared with experimental data. Current distribution measurements were carried out over a wide range of operating conditions and compared with the equivalent circuit model in order to determine the governing physics of the discharge and verify the existence of a deflagration at all tested conditions.

PR1 85 Effect of Li in the ITER neutralizer FRANCK DURÉ, TIBERIU MINEA, GILLES MAYNARD, *Laboratoire de Physique des Gaz et des Plasmas - Orsay France* AGUSTIN LIFSCHITZ, *Laboratoire d'Optique Appliquée Palaiseau France* Recently, a new design for the neutralizer stage of the ITER neutral beam injector has been proposed. Using Li instead of D2 gas. The gas load could be reduced by the use of a metal vapor easily frozen by surfaces and cryogenic pumping limitations would be exceeded allowing the accumulation of a thicker layer. This characteristic depends on the vaporization temperature of the lithium at low pressure ($\sim$0.1 Pa). Calculations showed the efficiency of the beam neutralization and the beam focusing. PIC simulations with the code OBI-2 (Orsay Beam Injector–2D) have shown the formation of a plasma between the neutralizer plates. It was also found that the positive ions of the plasma screen efficiently the beam space charge so that the beam divergence is reduced. The injection of Li has been investigated and compared to D2 one. Parametric study of the Li based neutralizer has been performed since the length and/or density of Li injected can be modified. The Li density profile has been estimated through Monte-Carlo 3D code developed in the LPGP. The resulted profile has been implemented as an input of the PIC-MCC code and results are presented.

PR1 86 PLASMA DATA EXCHANGE PROJECT

PR1 87 Comparisons of sets of electron-neutral scattering cross sections and calculated swarm parameters in N2 and H2 LEANNE PITCHFORD, G.J.M. HAGELAAR, S. PANCHESHNYI, M.C. BORDAGE, *LAPLACE, CNRS and Univ Toulouse, France* L.L. ALVES, C.M. FERREIRA, *IPFN/IST-UTL Lisbon, Portugal* S.F. BIAGI, *Univ Liverpool, UK* Y. ITIKAWA, *Inst of Space and Astronautical Sci, Japan* A.V. PHELPS, *JILA, NIST and Univ Colorado, USA* The GEC Plasma Data Exchange Project is an informal effort on the part of the low temperature plasma community to organize the collection, evaluation, and distribution of data both for modeling and for interpretation of experiments. In the context of this project, we present a description of the four sets of independently-compiled, electron-neutral scattering cross sections for N2 and for H2 presently available on the open-access LXCat site (www.lxcat.net). These sets are complete in that the main momentum and energy loss processes are taken into account, if we can neglect internal excitation in the gas. Three of these sets were derived using the requirement that they be consistent with available experimental swarm data, and the fourth set consists of recommended values from beam experiments and theory. To assess the validity of each of these cross section sets for use in modeling low temperature plasmas, we calculated electron transport and rate coefficients using these cross sections as input and compared with measured values also available on the LXCat site. We will discuss the influence of rotational temperatures between 77 and 300 K, and we again confirm that a two-term Boltzmann solver yields results in very good agreement with Monte Carlo simulations.

PR1 88 Comparisons of sets of electron-neutral scattering cross sections and calculated swarm parameters in O2 LEANNE PITCHFORD, M.C. BORDAGE, G.J.M. HAGELAAR, S. PANCHESHNYI, *LAPLACE, CNRS and Univ Toulouse, France* S.F. BIAGI, *Univ Liverpool, UK* Y. ITIKAWA, *Inst of Space and Astronautical Sci, Japan* I. KOCHETOV, A. NAPARTOVICH, *SRC TRINITI, Russia* A.V. PHELPS, *JILA, NIST and Univ Colorado, USA* The purpose of this communication is to describe the four independently-compiled sets of electron-O2 scattering cross section sets that are presently available on the LXCat site (www.lxcat.net). Three of these cross section sets were assembled and adjusted for good agreement with swarm parameters, and the fourth set consists of recommended data resulting from an evaluation of beam experiments and available theoretical. The cross sections sets are intended to be "complete" in the sense that the major electron energy, momentum, and number changing processes are taken into account, but it should be noted that the electronically excited levels included in the compilations differ from one cross section data set to another. We use these different data sets as input to a Boltzmann equation solver and calculate the electron transport and rate coefficients. Comparisons of calculated transport and rate coefficients with experimental data will be presented for each cross section set. We note that the consistency of the experimental data in O2 is not as good as the data for H2 and N2 (see previous poster). Some cross section data for electron scattering from Reactive Oxygen Species (ROS) are also available on LXCat.

PR1 89 Interpretation of calculated transverse and longitudinal diffusion for electrons in gases A.V. PHELPS, *JILA and National Inst. of Standards and Technology* G.J.M. HAGELAAR, *LAPLACE, CNRS and Universite de Toulouse, France* Ratios of transverse D_T and longitudinal D_L diffusion coefficients to mobility μ and mean energies for electrons in gases are calculated for a wide range of E/N for He, Ar, Xe, H_2, N_2, and CO. These transport coefficients are determined from spatial-gradient expansion, two-term spherical harmonic theory*,† and from Monte Carlo simulations.‡,§ As predicted by simplified theory‖ applied to the heavier rare gases, e.g., Ar and Xe, the ratio D_T/D_L reaches 7 to 10 at mean electron energies for which the momentum transfer cross sections are rapidly rising functions of energy. Comparisons are made of simplified# and detailed predictions of D_L/D_T values for N_2 and CO at low electron energies where the effects of scattering by the quadrupole potential of N_2 versus the dipole/quadrupole potential of CO are expected to be observed.

*J. H. Parker and J. J. Lowke, Phys. Rev. **181**, 290 (1969).
†G. J. M. Hagelaar (unpublished codes, 2012).
‡Ibid.
§S. F. Biagi, Nucl. Instr. and Meth. A **421**, 234 (1999).
‖Parker, Lowke, Op. cit.
#Ibid.

PR1 90 Quantemol-N calculation of electron molecule cross sections and related parameters WILL BRIGG, ADAM WILLIAMS, DEREK MONAHAN, JONATHAN TENNYSON, *University College London* Quantemol-N was originally developed as a wrapper for the UK Molecular R-Matrix codes, significantly accelarating data production rates for electron molecule collision calculations. Since its conception Quantemol-N has continuously been developed in the direction of the plasma industry, with many features being added to produce extended cross sections sets and related parameters. Recent additions include the calculation of differential cross sections, which provide momentum transfer and rotational excitation cross sections. These are used in turn to provide transport coefficients for verification of swarm calculations. Electron collisions with water have been used as a test bed. The code has also been generalised to calculate cross sections for aligned molecules, for example ones trapped on surfaces.

PR1 91 WORKSHOP POSTERS

PR1 92 Noninertial Multirelativity FLORENTIN SMARANDACHE, *University of New Mexico, Gallup Campus* We firstly propose an extension of Einstein's thought experiment with atomic clocks of the Special Theory of Relativity: considering non-constant accelerations and arbitrary $3D$-curves for both a particle's speed and trajectory inside the rocket and respectively the rocket's speed and trajectory. And secondly we propose as research multiple reference frames $F_1, F_2, ..., F_n$ moving on respectively arbitrary $3D$-curves $C_1, C_2, \ldots, C_n$ with respectively arbitrary non-constant accelerations $a_1, a_2, \ldots, a_n$ and respectively initial velocities $v_1, v_2, \ldots, v_n$. The reference frame F_i is moving with a nonconstant acceleration a_i and initial velocity v_i on a $3D$−curve C_i with respect to another reference frame F_{i+1} (where $1 \leqslant i \leqslant n\text{-}1$).

PR1 93 The effect of plasma jet on morphology of the apoptosis cancer cell SHAHRIAR MIRPOUR, *Laser-Plasma Research Institute of Shahid Beheshti University, Evin 1983963113, Tehran, Iran* MARYAM NIKKHAH, SOMAYE PIROUZMAND, *Department of Nanobiotechnology, Faculty of Biological Sciences, Tarbiat Modares University, Tehran, Iran* HAMID REZA GHOMI, *Laser-Plasma Research Institute of Shahid Beheshti University, Evin 1983963113, Tehran, Iran* In recent years, many studies have been carried out to understand the effect of non-thermal plasma on cancer cells. The previous studies showed that non-thermal plasma has apoptosis effect on cancer cells. Also they discovered that after plasma treatment three distinct regions (Death cells, Void zone and live cells) were observed in wells treated [1]. The aim of this paper is to study the effect of plasma jet on these three regions. For this purpose a variable voltage power supply with 20 kHz frequency are used experimentally. The results showed the detached cells rate were increased by increasing the voltage.

[1]A. Shashurin, M. Keidar, S. Bronnikov, R. A. Jurjus, and M. A. Stepp, Appl. Phys. Lett. **93**, 181501 (2008), DOI:10.1063/1.3020223

PR1 94 Verification of particle-in-cell simulations with Monte Carlo collisions M.M. TURNER, *Dublin City University, Ireland* Verification is the process of accumulating evidence that a computer simulation code is correct. For computer simulations in the physical sciences, this is usually understood to mean demonstrating that the results of a simulation correctly correspond to a solution of the underlying physical model. A particularly powerful way to accomplish this is by comparison with an exact solution or solutions of the physical model. When no single solution that exercises every part of the simulation programme exists, one can seek to develop a suite of solutions that in combination exercise all parts of the code. When a code correctly reproduces such a suite of solutions, one can feel a high degree of confidence that no errors are present. This paper discusses the verification of a particle-in-cell simulation with Monte Carlo collisions using this approach.

SESSION PR3: POSITRONS AND COLLISION PROCESSES IN PLASMAS
Thursday Morning, 25 October 2012; Room: Classroom 202 at 10:00; Tom Kirchner, York University, presiding

Invited Papers

10:00
PR3 1 On the modelling of positron transport in gases and soft-condensed biomaterials*
RON WHITE, *ARC Centre for Antimatter Matte Studies, James Cook University, Townsville, Australia*

The understanding and optimization of positron technologies such as Positron Emission Tomography requires a fundamental understanding of the underpinning physical processes involved, including accurate knowledge of the input positron scattering cross sections, material structure, and transport theories/simulations. The availability of new accurate and more complete sets of positron interaction cross sections has facilitated new theoretical investigations of positron transport. In this presentation we will highlight recent attempts to validate the accuracy and completeness of cross-sections through comparison with available swarm data. Comparisons between electron and positron transport will be presented and the importance of the positronium formation process on transport highlighted. As we progress towards a model of transport in soft-condensed systems (e.g. human tissue), we will discuss the theoretical formalism and present preliminary results for the transport and relaxation of positrons in dense gaseous and soft-condensed systems in spherical geometry. In particular a multi-term Boltzmann equation solution and associated eigenfunction treatment will be compared to a Monte-Carlo simulation. In these systems, the structure of the medium and effects of coherent scattering plays a significant role and we will highlight how this theory will need to be modified to consider biological polar liquids such as liquid water.

*Support: Australian Research Council Acknowledgements: R. E. Robson, G. Boyle, W. Tattersall, S. Dujko, Z. Lj. Petrovic, S. J. Buckman, G. Garcia, and M. J. Brunger.

Contributed Papers

10:30
PR3 2 Search for Positron Bound States in the Doubly Excited Region of the Helium Atom* ROISIN BOADLE, JOSHUA MACHACEK, EMMA ANDERSON, JAMES SULLIVAN, STEPHEN BUCKMAN, *CAMS, Australian National University, Canberra* Positron-atom binding has been the subject of many theoretical calculations in recent years. In these systems, a positron becomes temporarily bound to the atom, either through polarisation of the electronic charge cloud or formation of positronium (an e^-e^+ pair) which is weakly bound to the atom. There is now theoretical evidence of numerous positron-atom bound states, including for the helium atom. Ground state helium is incapable of binding a positron; however, recent calculations [1] have indicated that excited metastable states and doubly excited states may do so. These bound states might be expected to manifest themselves as structure in the energy dependence of the cross sections for processes such as total scattering, positronium formation, or ionization. We have carried out an experimental search for these positronic helium states in the doubly-excited region near 58 eV, using our high-resolution, trap-based positron beam. Results from this study will be presented and their ramifications discussed.

*This work is supported by the ARC.

[1]M. J. Bromley and J. Mitroy, Private Communication (2012).

10:45
PR3 3 Recent progress in understanding positron annihilation on molecules* A.C.L. JONES, J.R. DANIELSON, M.R. NATISIN, C.M. SURKO, *University of California, San Diego* Annihilation at positron energies in the range of the molecular vibrational modes is dominated by large-amplitude vibrational Feshbach resonances (VFR) in which the positron attaches to the molecule.[†] Recently, a broad spectrum of enhanced annihilation has been discovered and is observed in the spectra of many, if not most, molecules.[‡] This spectral component, known as statistical multimode resonant annihilation (SMRA), dominates the spectra in small molecules with relatively large binding energies, such as CCl_4 and CBr_4. Incorporation of an SMRA spectral component has allowed for a more accurate probe of VFR magnitudes and is providing insight into the process of intramolecular vibrational redistribution (IVR), through which VFRs can be either enhanced or suppressed.

*Work supported by NSF grant PHY 1068023.

[†]G. F. Gribakin, J. A. Young, and C. M. Surko, Rev. Mod. Phys. **82**, 2557 (2010).
[‡]A. C. L. Jones *et al.*, Phys. Rev. Lett. **108**, 093201 (2012).

Invited Papers

11:00

PR3 4 Positron plasma techniques and the production of a positronium gas
DAVID CASSIDY, *University of California*

The use of buffer gas positron traps has led to numerous advances in the field of positron physics, including improved beams for measurements of positron scattering from atoms and molecules, the production of antihydrogen and the generation of high-density positron pulses. The latter has been used to study dense positronium (Ps), in particular Ps-Ps scattering and the formation of molecular positronium, Ps_2. The ability to create non-neutral positron plasmas has played a key role in such experiments; using the rotating wall technique in the strong drive regime [Danielson and Surko, PRL **94**, 035001] allows for precise control of the positron density as well as very long confinement times. Here I shall outline the methods we have used to produce intense bursts of dense Ps and consider what we can do using these techniques in the future.

Contributed Papers

11:30

PR3 5 Electron attachment to halogenated alkenes and alkanes, 300–600 K* THOMAS M. MILLER, JEFFREY F. FRIEDMAN, NICHOLAS S. SHUMAN, ALBERT A. VIGGIANO, *Air Force Research Laboratory* Rate coefficients (k_a) and ion product distributions have been measured for 14 alkenes and alkanes with bromine, fluorine, and iodine substituents over the temperature range T = 300–600 K using a flowing-afterglow Langmuir-probe apparatus (FALP), most for the first time. Among these are 3 isomers of C_3F_5Br and 2 isomers of C_3F_7I. Four dibromide compounds yield Br_2^- in addition to Br^-. The results follow the expected trends: k_a values near the capture limit decrease slightly with T according to Vogt-Wannier theory, while k_a increase with T for molecules which have small k_a at 300 K. The results are analyzed using a statistical kinetic modeling approach, which is able to reproduce k_a values and product branching within experimental uncertainty. The modeling indicates that factor of 2 differences in k_a for the isomeric species can be explained by subtle variations in the potential surfaces.

*U.S. Air Force Office of Scientific Research Project AFOSR-2303EP.

11:45

PR3 6 Collisional dissociative recombination in helium-hydrogen afterglow plasmas RAINER JOHNSEN, *University of Pittsburgh* The puzzling dependence of electron-ion recombination in helium-hydrogen afterglows on neutral* and electron† densities is shown to be compatible with the "Collisional Dissociative Recombination" mechanism, originally proposed by Collins,‡ in which three-body capture of electrons into molecular high Rydberg states of H_3^+ leads to predissociation of the molecular core. While both electrons and neutrals play a role in the three-body capture, their effects on recombination do not add in a simple manner, which makes it difficult to distinguish three-body and binary dissociative recombination. Collision-induced angular momentum mixing (l-mixing), invoked in earlier models, also occurs but does not provide the rate-limiting step that controls the overall recombination rate.

*Glosík *et al.*, Phys. Rev. A **79**, 052707 (2009).
†Gougousi *et al.*, Int. J. Mass Spec. Ion Proc. **149-150**, 131 (1995).
‡Collins, Phys. Rev. A **140**, 1850 (1965).

SESSION QR1: PLASMA MODELING AND SIMULATIONS II

Thursday Morning, 25 October 2012; Room: Amphitheatre 204 at 10:30; Thomas Mussenbrock, Ruhr-Universität Bochum, presiding

Invited Papers

10:30

QR1 1 Atomic and Molecular Input Data for Plasma Modelling: a user's perspective
JAN VAN DIJK, *Eindhoven University of Technology*

With the advent of cheap, yet powerful computers, self-consistent numerical simulation has become a viable tool for understanding, designing and improving technological and scientific plasma sources. Nowadays, multi-dimensional models that are capable of simulating time-dependent discharge behaviour are in use at various universities and research institutes. One such computer code is Plasimo, a PLAsma SImulation MOdel that is being developed at Eindhoven University of Technology (http://plasimo.phys.tue.nl). Plasimo provides kinetic (Monte Carlo), hybrid and fluid models for transport-sensitive and equilibrium plasma. It is obvious that codes like Plasimo require a multitude of input data to function properly, but the measurement or calculation of such data is mostly outside the project's reach. In this contribution we, as Plasimo developers, will therefore provide a user's perspective of the subject of atomic and plasma data. In the first part of this contribution, we will provide an overview of the various sorts of input data that are needed for the types of plasma modelling that are supported by Plasimo. The discussion will be guided by real-world examples of models for low- and high-pressure plasma sources. In the second part of the contribution, we will discuss how modern Internet technologies can help us to fulfill our input data needs. As of today, input data are typically either hard-coded in computer programs, or read from local input files. Moreover, data pre-processing tasks, like integrating cross sections to rate coefficients, are usually carried out locally as well. We will demonstrate how Web Services (http://www.w3.org/2002/ws/) can be used to manage, disseminate and manipulate data sets more conveniently. We will also identify various input data pre-processing tasks that could be taken over by data distributors, suggest how this could be implemented, and sketch the work flow that would result from such effort.

Contributed Papers

11:00

QR1 2 Multi-Peaked and Stepped Electron Velocity Distributions in RF-DC Discharges with Secondary Emission A.V. KHRABROV, I.D. KAGANOVICH, *Princeton Plasma Physics Laboratory* D. SYDORENKO, *University of Alberta* E.A. STARTSEV, *Princeton Plasma Physics Laboratory* L. CHEN, P. VENTZEK, R. SUNDARARAJAN, *Tokyo Electron America* A. RANJAN, K. KUMAR, *Tokyo Electron Technology Center America* E. TOKLUOGLU, *Princeton Plasma Physics Laboratory* In RF-DC (hybrid) capacitive-coupled discharges, secondary electrons emitted from the electrodes undergo a complicated motion defined by acceleration in, and bouncing between a steady and an oscillating sheath. For the electrons that return to the RF electrode, the arrival phase is a multi-valued function of the phase in which they were emitted. This basic property leads to a velocity distribution with multiple peaks. The phase of arrival can also be discontinuous, which corresponds to a distribution containing steps. We have observed such distributions in numerical test-particle simulations, and analyzed the observed structure of the electron distributions.

11:15

QR1 3 Simulation of an Atmospheric Pressure Plasma Jet in a Stagnation Flow DOUG BREDEN, LAXMINARAYAN RAJA, *University of Texas at Austin* Pulsed atmospheric pressure plasma jets (APPJs) have generated significant interest for their ability to generate non-thermal plasma in open air gaps without the risk of arcing. The plasma typically forms due to a sequence of fast ionization waves which propagate within a noble gas jet exhausting into ambient air. The resulting luminous plasma plume is safe to touch due to the non-equilibrium nature of the plasma and low gas temperatures. At the same time, high energy electrons in the ionizing head can generate reactive radical species (N and O) in addition to ions and UV radiation, which may be beneficial for biomedical applications. In order to gauge the effectiveness of these jets for treating surfaces, it is desirable to know how the plasma jet interacts with a surface and the flux of reactive species to that surface. In this work, the propagation of a single ionization wave in the stagnation flow of a helium jet impinging on a solid surface is modeled. The plasma discharge dynamics are modeled using a self-consistent, two temperature plasma solver with finite rate chemistry. The helium-jet stagnation flow is modeled using a compressible, multiple species Navier-Stokes solver. The primary objective is to determine the net delivery of reactive species to the surface and the role of parameters such as dielectric thickness.

11:30

QR1 4 1D Microscale Breakdown Simulations using an Energy-Conserving, Implicit PIC-DSMC Method* CHRIS MOORE, MATTHEW HOPKINS, PAUL CROZIER, EDWARD BARNAT, JEREMIAH BOERNER, RUSSELL HOOPER, MATTHEW BETTENCOURT, LAWRENCE MUSSON, *Sandia National Laboratories* An energy and charge conserving fully implicit formulation for electrostatic particle-in-cell (PIC) simulations with complex boundary conditions and direct simulation Monte Carlo (DSMC) particle collisions is used in this work to simulate atmospheric breakdown in small gaps. This method allows for energy conservation with arbitrarily large field-solve timesteps limited only by dynamic timescales. Momentum errors are reduced through the use of adaptive sub-stepping of the particle motion over the field-solve timestep allowing for vastly different ion and electron timesteps. Simulations of one dimensional direct current breakdown between two electrodes including electron-neutral elastic, ionization, and excitation interactions and emission of electrons from the cathode via Auger neutralization and field electron emission are presented here. The dynamics of breakdown are investigated and the breakdown voltages deviate from the Paschen curve if the Fowler-Nordheim emission flux is based on the near surface field which includes space charge effects. It is found that, early on, the primary electron generation mechanism at breakdown voltage changes from ionization/Auger neutralization in large gaps to Fowler-Nordheim emission in small gaps.

*Sandia National Laboratories is a multi-program lab managed by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. DOE's NNSA under contract DE-AC04-94AL85000.

11:45

QR1 5 Simulation of the Partially Ionized Reacting Plasma Flow in a Negative Hydrogen Ion Source* NIKOLAOS GATSONIS, SERGEY AVERKIN, *WPI* LYNN OLSON, *Busek Co. Inc.* A High Pressure Discharge Negative Ion Source (HPDNIS) operating on hydrogen is been under investigation. The Negative Ion Production (NIP) section of the HPDNIS attaches to the 10–100 Torr RF-discharge chamber with a micronozzle and ends with a grid that extracts the negative ion beam. The partially ionized and reacting plasma flow in the NIP section is simulated using an unstructured three-dimensional Direct Simulation Monte Carlo (U3DSMC) code. The NIP section contains a low-pressure plasma that includes H_2, vibrationally-rotationally excited H_2^*, negative hydrogen atoms H^-, and electrons. Primary reactions in the NIP section are dissociate attachment, $H_2^* + e \rightarrow H^0 + H^-$ and electron collisional detachment, $e + H^- \rightarrow H + 2e$. The U3DSMC computational domain includes the entrance to the NIP nozzle and the extraction grid at the exit. The flow parameters at the entrance are based on conditions in the RF-discharge chamber and are implemented in U3DSMC using a Kinetic-Moment subsonic boundary conditions method. The rotational and vibrational degrees of freedom in U3DSMC are implemented using the Larsen-Borgnakke model. Chemical reactions are implemented in U3DSMC using the Quantum-Kinetic model. Simulations cover the regime of operation of the HPDNIS and examine the flow characteristics inside the NIP section.

*Supported by the Department of Energy.

12:00

QR1 6 Inductive Plasma Discharge Modeling of a Micro Newton Radiofrequency Ionthruster (μN-RIT) ROBERT HENRICH, CHRISTIAN HEILIGER, *Justus-Liebig-University, I. Physikalisches Institut* Up to date challenging scientific space experiments like LISA to detect gravitational waves have high requirements especially for the thruster. One of the most promising thruster is the μN-RIT developed at the University of Giessen. This type uses an inductive plasma discharge and an extraction grid system for accelerating the ions up to a few keV. Due to this the μN-RIT fulfills the requirements of a wide range of thrust as well as the high precision of it. Also the magnitude of the power consumption is limited to about 10 W. This is slightly below of actually μN-RIT values. To meet this limitation the plasma modeling is an absolutely essential tool. The typical gas pressure in such a system is about 0.1 Pa. As a consequence validity of fluid dynamics is not guaranteed and a Particle in Cell (PIC) method could be necessary. However, PIC causes an enormous calculation consumption. Therefore, we are performing both kinds. For the fluid modeling we use the "Comsol Multiphysics" tool and for the PIC modeling we are developing a three dimensional massive parallelized code using MPI for all parts of the simulation. We present our first simulation results. Moreover, we compare the results of both tools and show how far the fluid simulation differs from the PIC simulation.

12:15

QR1 7 Modeling PECVD of photovoltaic silicon layers from hydrogen diluted silane ccrf discharges* DIRK BLUHM, STEPHAN DANKO, OLIVER SCHMIDT, *Robert Bosch GmbH, Stuttgart* RALF PETER BRINKMANN, *Ruhr-University Bochum* The dynamic photovoltaic market (especially for thin film technologies) demands massive cost reduction and efficiency increase. Plasma processes play a crucial role in various solar cell technologies. Desired high quality silicon films must be deposited fast and under stable process conditions. We use a commercial fluid model (CFD-ACE+)† to obtain spatiotemporal species densities and reaction rates. The chemical data set comprises of around 20 species and 80 chemical reactions. Densities obtained with a fast volume-averaged chemical model show good agreement with bulk densities from the fluid model. Care must be taken not to over-simplify chemical reaction mechanisms at pressures above 200 Pa, when polymerization processes become increasingly important. We study deposition regimes over a wide range of parameters, varying the pressure between 50 and 1000 Pa and allowing for high frequencies up to 95 MHz. Different heating mechanisms can be distinguished, leading to a different localization of radical generation. This is particularly relevant for asymmetric discharges. Process dependent radical composition and ion bombardment are analyzed, leading to design rules. Investigation of the ion bombardment by modeling the plasma sheath independently will be a subject of further research.

*Support from the German Federal Ministry of Environment (BMU), project No. 0325260A, is gratefully acknowledged.

†CFD-ACE+ User Manual, v2010.0, ESI Group, http://www.esi-cfd.com.

SESSION QR2: NON-EQUILIBRIUM KINETICS
Thursday Morning, 25 October 2012
Room: Classroom 203 at 10:30
Mirko Vukovic, Tokyo Electron Limited, presiding

Contributed Papers

10:30

QR2 1 Reactive species in atmospheric pressure helium-oxygen plasmas with humid air impurities* TOMOYUKI MURAKAMI, *Tokyo Institute of Technology* KARI NIEMI, TIMO GANS, DEBORAH O'CONNELL, *University of York* WILLIAM G. GRAHAM, *Queen's University Belfast* In most applications helium-based plasma jets operate in an open air environment. The presence of humid-air in the plasma jet will influence the plasma chemistry and can lead to the production of a broader range of reactive species. We explore the influence of humid air on the reactive species in rf driven atmospheric-pressure helium-oxygen mixture plasmas (helium with 5000 ppm admixture of oxygen) for wide air impurity levels of 0-500 ppm with relative humidities of from 0 to 100% using a zero-dimensional, time-dependent global model. Comparisons are made with experimental measurements in an rf driven micro-scale atmospheric pressure plasma jet and with one-dimensional semi-kinetic simulations of the same plasma jet. The evolution of species concentration is described for reactive oxygen species, metastable species, radical species and positively- and negatively-charged ions (and its clusters). Effects of the air impurity containing water humidity on electronegativity and chemical activity are clarified with particular emphasis on reactive oxygen species.

*Supported by JSPS Innovative Areas (24110704) and (C) (24561054) and UK EPSRC Career Acceleration Fellowship (EP/H003797/1) and Science and Innovation Award (EP/D06337X/1).

10:45

QR2 2 Influence of kinetic effects on the resonance behavior of the Multipole Resonance Probe* JENS OBERRATH, THOMAS MUSSENBROCK, RALF PETER BRINKMANN, *Theoretical Electrical Engineering, Ruhr University Bochum* Active plasma resonance spectroscopy is a well known diagnostic method. Many concepts of this method are theoretically investigated and realized as a diagnostic tool. One of these tools is the multipole resonance probe (MRP) [1]. The application of such a probe in plasmas with pressures of only a few Pa raises the question whether kinetic effects have to be taken into account or not. To address this question a kinetic model is necessary. A general kinetic model for an electrostatic concept of active plasma resonance spectroscopy has already been presented by the authors [2]. This model can be used to describe the dynamical behavior of the MRP, which is interpretable as a special case of the general model. Neglecting electron-neutral collisions, this model can be solved analytically. Based on this solution we derive an approximated expression for the admittance of the system to investigate the influence of kinetic effects on the resonance behavior of the MRP.

*The authors acknowledge the support by the Deutsche Forschungsgemeinschaft (DFG) via the Ruhr University Research School and the Federal Ministry of Education and Research in frame of the PluTO project.

[1] M. Lapke *et al.*, Plasma Sources Sci. Technol. **20**, 042001 (2011).
[2] J. Oberrath *et al.*, Proceedings of the 30th International Conference on Phenomena in Ionized Gases, 28th August - 2nd September, 2011.

11:00

QR2 3 Influence of cross section set on the self-consistent electron and vibrational kinetics* GIANPIERO COLONNA, MARIO CAPITELLI, *CNR-IMIP Bari* CNR-IMIP BARI TEAM Advanced models of elementary processes in plasmas are based on the self–consistent approach, solving at the same time the Boltzmann equation for free electrons and the master equation for the evolution of species concentration and the distribution of internal state. In some conditions, it is very important also to couple these models with the radiation transport, to consider non–local effects, because the radiation emitted in one location can be absorbed in a different position. This aspects is very important in high pressure, conditions met in high pressure pulsed discharges. The new set of e-molecule cross sections, extend the available data, considering processes for the whole vibrational ladder, has dramatic effects on the kinetics, increasing considerably the energy injected in internal degrees of freedom. This work is intended to investigate such effects, comparing results obtained by using old cross section set or recently calculated complete set.

*Funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 242311.

11:15

QR2 4 Production and provision mechanisms of OH radical of an atmospheric-pressure helium plasma jet SEIYA YONEMORI, RYO ONO, TETSUJI ODA, *The University of Tokyo* THE UNIVERSITY OF TOKYO TEAM An atmospheric-pressure helium plasma jet is getting much attention because of its low heat load. It is known that active species such as OH radical play important role in many plasma processes, for example, in plasma medical care or in plasma sterilization. When using the plasma jet for surface treatment, it is important that the amount of OH radical provided into objectives. We measured OH density in the vicinity of the surface of objectives using laser induced fluorescence (LIF). The plasma jet was generated when AC 8 kHz, 10 kV was applied. When the plasma jet extended onto the dry glass surface, the maximum OH density was 0.2 ppm. On the other hand, the maximum OH density was 1 ppm when the plasma jet extended onto the wet surface. In addition, time-evolution of OH density between two successive voltage pulses was measured. On the edge of the plasma jet, OH density was at maximum and rapidly decreased between two pulses. Those results suggest that there are three ways of OH production; first, the dissociation of H_2O included in discharge gas; secondly, the dissociation of H_2O included in the ambient air; finally, the dissociation of H_2O evaporates from the wet surface.

11:30

QR2 5 Thermal electron attachment to fluorocarbon radicals: Experiment and kinetic modeling NICHOLAS SHUMAN, THOMAS MILLER, ALBERT VIGGIANO, *Air Force Research Laboratory* Few experimental measurements of the kinetics of electron attachment to radicals exist due to the inherent difficulties of working with transient species. Electron attachment to small fluorocarbon radicals is particularly important, as the data are needed for predictive modeling of plasma etching of semiconductor materials. We have recently developed a novel flowing afterglow technique to measure several types of otherwise difficult to study plasma processes, including thermal electron attachment to radicals. Variable Electron and Neutral Density Attachment Mass Spectrometry (VENDAMS) exploits dissociative electron attachment in a weakly ionized plasma as a radical source. Here, we apply VENDAMS to a series of halofluorocarbon precursors in order to measure the kinetics of thermal electron attachment to fluorocarbon radicals. Results are presented for CF_2, CF_3, C_2F_5, CF_3, 1-C_3F_7, 2-C_3F_7, and C_3F_5 from 300 to 600 K. Both the magnitude and the temperature dependences of rate coefficients as well as product branching between associative and dissociative attachment are highly system specific. The data are analyzed using a kinetic modeling approach, allowing for physical insight into the systems as well as extrapolation to non-thermal conditions inaccessible to the experiment.

11:45

QR2 6 Ozone kinetics in low-pressure discharges* VASCO GUERRA, *Instituto de Plasmas e Fusao Nuclear, Instituto Superior Tecnico, Universidade Tecnica de Lisboa, Portugal* DANIIL MARINOV, OLIVIER GUAITELLA, ANTOINE ROUSSEAU, *LPP, Ecole Polytechnique, UPMC, Universite Paris Sud-11, CNRS, Palaiseau, France* Ozone kinetics is quite well established at atmospheric pressure, due to the importance of ozone in atmospheric chemistry and to the development of industrial ozone reactors. However, as the pressure is decreased and the dominant three-body reactions lose importance, the main mechanisms involved in the creation and destruction of ozone are still surrounded by important uncertainties. In this work we develop a self-consistent model for a pulsed discharge and its afterglow operating in a Pyrex reactor with inner radius 1 cm, at pressures in the range 1–5 Torr and discharge currents of 40–120 mA. The model couples the electron Boltzmann equation with a system of equations for the time evolution of the heavy particles. The calculations are compared with time-dependent measurements of ozone and atomic oxygen. Parametric studies are performed in order to clarify the role of vibrationally excited ozone in the overall kinetics and to establish the conditions where ozone production on the surface may become important. It is shown that vibrationally excited ozone does play a significant role, by increasing the time constants of ozone formation. Moreover, an upper limit for the ozone formation at the wall in these conditions is set at 10(-4).

*VG thanks the FCT funding to IPFN-LA.

SESSION QR4: MICRODISCHARGES II

Thursday Morning, 25 October 2012; Room: TBD at 10:30; Julian Schulze, Ruhr-Universität Bochum, presiding

Invited Papers

10:30

QR4 1 Modelling of capacitive microdischarges at atmospheric pressure
PASCAL CHABERT, *LPP, CNRS-Ecole Polytechnique*

A one-dimensional hybrid analytical-numerical global model of atmospheric pressure, radio-frequency (rf) driven capacitive discharges is developed. The feed gas is assumed to be helium with small admixtures of oxygen or nitrogen. The electrical characteristics are modeled analytically as a current-driven homogeneous discharge. The electron power balance is solved analytically to determine a time-varying Maxwellian electron temperature, which oscillates on the rf timescale. Averaging over the rf period yields effective rate coefficients for gas phase activated processes. The particle balance relations for all species are then integrated numerically to determine the equilibrium discharge parameters. The coupling of analytical solutions of the time-varying discharge and electron temperature dynamics, and numerical solutions of the discharge chemistry, allows for a fast solution of the discharge equilibrium. Variations of discharge parameters with discharge composition and rf power are determined. Comparisons are made to more accurate but numerically costly fluid models, with space and time variations, but with the range of parameters limited by computational time.

Contributed Papers

11:00

QR4 2 A novel global model for radio-frequency driven plasmas at atmospheric pressure* TORBEN HEMKE, THOMAS MUSSENBROCK, RALF PETER BRINKMANN, *Theoretical Electrical Engineering, Ruhr-Universitaet Bochum* Over the last years microplasma research gained a lot of attention both from an experimental and theoretical perspective. One particular type of microplasma sources that shows a variety of interesting physics and applications are the so called plasma jets. Besides the more elaborated fluid or hybrid approaches the so called global models offer the ability to explore averaged species densities and energies while remaining computationally efficient. This contribution investigates a coplanar radio-frequency driven plasma jet by means of a novel global model. The model takes into account the strong modulation of the electric field in time and space both in the sheath and bulk region. By means of a consistent scale analysis we find an analytical expression for the electric field. We compare our obtained electric field to results from PIC simulations and present the general concept for this novel global model of the microplasma jet.

*This work is supported by the German Research Foundation DFG in the frame of the Research Group FOR 1123 "Physics of microplasmas'."

11:15

QR4 3 Dynamics and structure of helium discharge in thin dielectric tubes at atmospheric pressure JAROSLAV JANSKY, ANNE BOURDON, *Laboratory EM2C, Ecole Centrale Paris, Grande voie des vignes, 92295 Chatenay-Malabry, France* Since a few years, atmospheric pressure plasma micro-jets formed by pulsed helium discharges ignited in thin dielectric tubes have received considerable interest due to their potential for biomedical applications. So far, most experimental and simulation works have been dedicated to the study of the plasma plume. Recently, to better understand the ignition and dynamics of plasma jets, different experiments have been done to study the discharge inside tubes and close to the tube exit. In this work, we propose to simulate in 2D the discharge ignition and dynamics inside the tube. In particular we propose to discuss the influence of the electrode geometry and of nitrogen admixtures and to compare simulation results with recent experiments done by different research groups. In this work, the dynamics of surface charge deposition during the discharge propagation in the tube is studied. For repetitive voltage pulses, we propose to discuss the influence of some remaining surface charges from previous discharges on the subsequent discharge ignition. Finally, we propose to simulate the interaction of two discharges propagating towards each other in tubes and to compare results with experiments.

11:30

QR4 4 Line profile and translational temperature of Pb and metastable He atoms at middle pressures in micro hollow cathode discharge* MARI INOUE, *Wakayama University* TAKAYUKI OHTA, MASAFUMI ITO, *Meijo University* MASARU HORI, *Nagoya University* Hollow cathode discharges have been studied as light sources. Conventional hollow cathode discharges have been operated at low pressure, while micro hollow cathode discharges at near atmospheric pressure. At the middle pressures below 40 kPa, the emission of metallic atoms is observed due to sputtering. Moreover, the line profile of atom shits from a Gaussian to Voigt profile as increasing pressure. In this study, the behaviors of Pb and metastable He atoms in the micro hollow cathode discharge at pressures of the order of kPa have been investigated by diode laser absorption spectroscopy. The pressure broadening effect for absorption line-profile was overlapped to Doppler profile and was estimated to be 0.26 MHz/Pa for metastable He atoms in the range from 5 to 10 kPa. The translational temperature decreased from 830 to 410 K with increasing the pressure. For Pb atoms, the temperature decreased from 820 to 610 K with increasing He pressure from 4.9 to 7.4 kPa. The pressure broadening effect for Pb atom has been estimated to be 0.22 MHz/Pa.

*This work was partly supported by the Knowledge Cluster Initiative (the Second Stage) -Tokai Region Nanotechnology Manufacturing Cluster - from MEXT of Japan and a Grant-in-Aid for Young Scientists (B) (No. 22760561) from JSPS in Japan.

11:45

QR4 5 Characterization and Application of Microplasma Devices for Ambient Mass Spectrometry and Surface Analysis JOSHUA SYMONDS, REUBEN GANN, THOMAS ORLANDO, *Georgia Institute of Technology* In ambient mass spectrometry, ionization sources with broad chemical compatibility, low fragmentation, and high reliability are one of the keys necessary to enable effective and rapid analysis of unknown samples. One such approach, employing a variety of ambient-pressure microplasma discharges, has demonstrated itself to be a promising technique with a variety of successful applications and results. This class of devices holds a competitive edge over alternative ambient ionization methods when cost and portability are a concern: microplasmas typically require only modest electrical power and minimal gas flows to operate. We have developed our own such devices and methods, and look more closely into the physical nature of what makes particular designs successful. We focus on the development of these devices to perform mass spectrometry imaging in tandem with optical microscope imaging of samples at ambient pressure. Additionally, we investigate the use of microplasma devices for production of VUV photons, another highly effective ionization source.

SESSION RR2: THERMAL PLASMAS: ARCS, JETS, SWITCHES, OTHERS

Thursday Afternoon, 25 October 2012
Room: Classroom 203 at 13:30
Mark Cappelli, Stanford University, presiding

Contributed Papers

13:30

RR2 1 Electrothermal Characterization of an AC Thermal Plasma Torch ALEXANDER ZIELINSKI, *TezlaTec* HARRY FAIR, REGINALD ALLEN, *Institute for Strategic and Innovative Technologies, Austin, TX* TREY GEBHART, LEIGH WINFREY, *Virginia Polytechnic Institute, Department of Mechanical Engineering, Blacksburg, VA* JOSHUA NOWAK, MOHAMED BOURHAM, *North Carolina State University, Department of Nuclear Engineering, Raleigh, NC* A primary component in gasification is the plasma torch. Conversion of electrical energy to a high-temperature arc is essential. The properties of this arc determines, among other things, the efficiency of converting electrical input power to heat and mass transfer in the reactor chamber. A unique, single-phase torch was acquired for gasification studies. Power for this torch is supplied from the electric mains and is stepped up to 6 kV. The torch uses gas flow to complement the electrical energy transfer. Electrical operation of the torch is characterized by the Volt-Ampere plot, which is useful in determining the power rating of the torch as well as diagnosing the dynamic behavior of the plasma. The output of the torch is a thermal source at or near local thermodynamic equilibrium (LTE). Diagnostics are employed to characterize the torch. Plasma current is obtained by using a current transformer. Measurement of the plasma voltage is via an isolated technique. Optical emission spectroscopy, with the assumption of LTE, is used to determine the plasma kinetic temperature using the relative line method. An electrothermal plasma code provides the fundamental parameters at the torch nozzle, which are needed for gasification reactor design.

13:45

RR2 2 Numerical modeling of deflagration mode in coaxial plasma guns HARISWARAN SITARAMAN, LAXMINARAYAN RAJA, *University of Texas, Austin* Pulsed coaxial plasma guns have been used in several applications in the field of space propulsion, nuclear fusion and materials processing. These devices operate in two modes based on the delay between gas injection and breakdown initiation. Larger delay led to the plasma detonation mode where a compression wave in the form of a luminous front propagates from the breech to the muzzle. Shorter delay led to the more efficient deflagration mode characterized by a relatively diffuse plasma with higher resistivity. The overall physics of the discharge in the two modes of operation and in particular the latter remain relatively unexplored. Here we perform a computational modeling study by solving the non-ideal Magneto-hydrodynamics equations for the quasi-neutral plasma in the coaxial plasma gun. A finite volume formulation on an unstructured mesh framework with an implicit scheme is used to do stable computations. The final work will present details of important species in the plasma, particle energies and Mach number at the muzzle. A comparison of the plasma parameters will be made with the experiments reported in Ref. [1].

[1]F. R. Poehlmann *et al.*, Phys. Plasmas **17**, 123508 (2010).

14:00

RR2 3 Speckle imaging of a circuit breaker arc near current-zero PATRICK STOLLER, RAPHAEL FÄRBER, EMMANOUIL PANOUSIS, MICHAEL SCHWINNE, *ABB Switzerland Ltd.* Optical speckle imaging can be used to determine quantitatively the temperature and density distribution in an axially symmetric gas flow by measuring the gradient of the index of refraction. This technique was applied to studying the properties of a high current arc embedded in a supersonic flow as the current approaches a zero-crossing. Such conditions play an important role in high voltage gas circuit breakers, where an arc is drawn between two contacts and axially blown to interrupt a current. A simple test device designed to reproduce the key features of a circuit breaker while allowing easy access for optical measurements was used. The arc was blown axially with synthetic air. Nozzles equipped with glass windows were used to permit speckle imaging of the flow; measurements were also carried out at the exit of the nozzle. The decaying phase of the high current arc was extended artificially by injecting a low DC current. Density and temperature information calculated from speckle images was coupled with arc voltage and current measurements and compared to CFD calculations to gain a better understanding of arc dynamics during the current-zero phase.

14:15

RR2 4 Numerical study on the Z pinch dynamics of gas jet type discharge produced plasma (DPP) source BIN HUANG, BIN XIE, TAKU TOMIZUKA, MASATO WATANABE, FENG XIAO, EIKI HOTTA, *Tokyo Institute of Technology* Z pinch DPP source is often used as an Extreme Ultra-Violet (EUV) source. It is convenient to produce high temperature and high density plasma. There are several analytical models to describe the dynamics of the plasma. The snowplow model is a simple and widely used model to analyze the motion of the plasma shell and predict the pinch time; however, it is incapable of analyzing the plasma behavior after the maximum pinch and providing detailed information of concerned plasma parameters, such as electron density and electron temperature. In this study, we present the simulation results of the Z pinch DPP dynamics obtained by a 2D MHD code. This code solves the problem based on the assumption of single fluid, two temperature approximations in the cylindrical geometry. The numerical scheme for this MHD code is Total-Variation-Diminishing scheme in Lax Friedrich formulation (TVD-LF). The evolution of electron density, electron temperature, current density, magnetic flux and some other important parameters in Z pinch dynamics are investigated with this code. The simulation results show that the maximum pinch electron density is on the order of 10^{19} cm^{-3}, with a pinch plasma radius of about 0.1 mm. In order to optimize the radiation output, the influences of initial gas distribution and the current waveform on the Z pinch dynamics are also investigated. They affect the electron density at pinch stagnation obviously; while in term of electron temperature, the effect is slight.

14:30

RR2 5 Role of external magnetic field and current closure in the force balance mechanism of a magnetically stabilized plasma torch RAVI G, VIDHI GOYAL, *Institute for Plasma Research, Gandhinagar, India* Experimental investigations on the role of applied external magnetic field and return current closure in the force balance mechanism of a plasma torch are reported. The plasma torch is of low power and has wall, gas and magnetic stabilization mechanisms incorporated in it. Gas flow is divided into two parts: axial-central and peripheral-shroud, applied magnetic field is axial and return current is co-axial. Results indicate that application of large external magnetic field gives rise to not only $\mathbf{J} \times \mathbf{B}$ force but also, coupled with gas flow, to a new drag-cum-centrifugal force that acts on the plasma arc root and column. The magnetic field also plays a role in the return current closure dynamics and thus in the overall force balance mechanism. This in turn affects the electro-thermal efficiency of the plasma torch. Detailed experimental results, analytical calculations and physical model representing the processes will be presented and discussed.

14:45

RR2 6 Spectroscopy of multicomponent thermal plasma ANTON LEBID,* ANATOLIY VEKLICH,† VIACHESLAV BORETSKIJ,‡ SERGIY FESENKO,§ ROSTISLAV SEMENYSHYN,‖ *Taras Shevchenko Kyiv National University, Kyiv, Ukraine* Applications of composite materials in switching devices for the electrical engineering industry stimulate the interest in studying of the arc discharge plasma between composite electrodes. As an industrial application of silver - cadmium oxide leads to the environmental pollution, the more attention must be paid to the development of composites, which contain alternate materials, in particular, Ag-SnO_2-ZnO. Composite materials on copper base with addition of high-melting metals, like tungsten and molybdenum, are widely used as well. The plasma parameters of free burning electric arc discharge between composite electrodes Ag-SnO_2-ZnO, Cu-Mo and Cu-W were obtained by optical emission spectroscopy. The radial profiles of temperature and electron density at different arc currents were obtained by spectroscopy techniques. These experimental results were used in calculation of plasma composition in assumption of local thermodynamic equilibrium. So, electric erosion properties of such kind materials were testified. The selection of CuI, AgI, ZnI, MoI and WI spectral lines and their spectroscopic data were carried out.

*postgraduate student
†PhD, associate professor, senior researcher
‡PhD, assistant lecturer
§postgraduate student
‖master student

SESSION RR3: PLASMA PROPULSION II

Thursday Afternoon, 25 October 2012; Room: Classroom 202 at 13:30; John Foster, University of Michigan, presiding

Invited Papers

13:30

RR3 1 Rotating spoke phenomena in low pressure E × B discharges*

YEVGENY RAITSES, *Princeton Plasma Physics Laboratory, Princeton, NJ 08543*

The rotating spoke is azimuthal plasma non-uniformity which has been observed in a variety of low pressure cross-field discharges of cylindrical geometry [1–3]. The spoke can appear in different modes ranging from m = 1 to higher order modes which propagate in the direction perpendicular to electric and magnetic fields with velocities of much lower than E×B velocity [2,3]. Although spoke phenomena is known for more than four decades, physical mechanism responsible for triggering of the spoke is still not understood. Recent studies of Hall thrusters and Penning-type magnetized plasma discharges demonstrated that the spoke is directly responsible for the enhancement of the electron cross-field transport in these devices [1,4]. A combination of time-resolving plasma measurements, including high speed imaging and probes suggest that for partially ionized magnetized plasma discharges, the spoke instability is triggered by ionization mechanism [4]. These experimental results are supported by recent particle-in-cell simulations. The advancement in understanding of the spoke mechanism enabled us to develop and demonstrate effective methods of spoke control, including mode, velocity and direction of the spoke, and spoke suppression [5]. Among practical implications of these results is the ability to develop more effective methods of plasma confinement and uniformity for magnetically-enhanced discharges and more efficient magnetized plasma thrusters. In collaboration with M. Griswold, L. Ellison, N. J. Fisch, K. Matyash, R. Schneider, and A. Smolyakov.

*This work was supported by the US DOE under Contract Number DE-AC02-09CH11466.

[1]S. Jaeger, Th. Pierre, and C. Rebont, Phys. Plasmas **16**, 022304 (2009).
[2]J. B. Parker, Y. Raitses, and N. J. Fisch, Appl. Phys. Lett. **97**, 091501 (2010).
[3]M. S. McDonald and A. D. Gallimore, IEEE Trans. Plasma Sci. **39**, 2952 (2011).
[4]C. L. Ellison, Y. Raitses, and N. J. Fisch, Phys. Plasmas **19**, 013503 (2012).
[5]M. E. Griswold, C. L. Ellison, Y. Raitses, and N. J. Fisch, Phys. Plasmas **19**, 053506 (2012).

Contributed Papers

14:00

RR3 2 Performance characterization of a permanent-magnet helicon plasma thruster KAZUNORI TAKAHASHI, *Iwate University* CHRISTINE CHARLES, ROD BOSWELL, *The Australian National University* Helicon plasma thrusters operated at a few kWs of rf power is an active area of an international research. Recent experiments have clarified part of the thrust-generation mechanisms. Thrust components which have been identified include an electron pressure inside the source region and a Lorentz force due to an electron diamagnetic drift current and a radial component of the applied magnetic field. The use of permanent magnets (PMs) instead of solenoids is one of the solutions for improving the thruster efficiency because it does not require electricity for the magnetic nozzle formation. Here the thrust imparted from a permanent-magnet helicon plasma thruster is directly measured using a pendulum thrust balance. The source consists of permanent magnet (PM) arrays, a double turn rf loop antenna powered by a 13.56 MHz rf generator and a glass source tube. The PM arrays provide a magnetic nozzle near the open exit of the source and two configurations, which have maximum field strengths of about 100 and 270 G, are tested. A thrust of 15 mN, specific impulse of 2000 sec and a thrust efficiency of 8 percent are presently obtained for 2 kW of input power, 24 sccm flow rate of argon and the stronger magnetic field configuration.

14:15

RR3 3 Collective Thomson scattering investigations of the Hall thruster plasma SEDINA TSIKATA, *ICARE, CNRS* CYRILLE HONORE, DOMINIQUE GRESILLON, *LPP, Ecole Polytechnique* NICOLAS LEMOINE, JORDAN CAVALIER, *Institut Jean Lamour, Universite de Lorraine* Anomalous electron transport outside the Hall thruster channel is believed to be due to plasma turbulence. Recent experiments using a specially-designed collective Thomson scattering diagnostic on a 5kW thruster have permitted the identification of a wave believed to be involved in transport. The observed properties of the mode, which is naturally driven by the fast azimuthal electron drift, are in line with predictions from PIC simulations and linear kinetic theory analysis. Detailed characterizations of mode properties, including dispersion relation, directivity, spatial extent and fluctuation amplitude have been obtained. These studies are now extended to consider the universality of mode features in a 200W permanent magnet Hall thruster and links between thruster performance, operating régimes and the presence of such a mode.

14:30

RR3 4 Effect of applied magnetic nozzle on an MPD Thruster AKIRA ANDO, YUKI IZAWA, KOHEI OKAWA, YOKO HASHIMA, HIROSHI WATANABE, NOZOMI TANAKA, *Grad. School of Engineering, Tohoku Univ.* Electric propulsion systems are suitable for long-term mission in space due to its higher specific impulse. An Magneto-Plasma-Dynamic Thruster (MPDT) is one of the promising thrusters of high power electric propulsion systems. It has been reported that the thrust performance of an MPDT can be improved by applying an axial magnetic field on it. In order to investigate the effect of applied field on an MPDT, we have investigated plume plasma parameters and thrust performance in an applied field MPDT. Different types of divergent magnetic nozzle were applied to an MPDT, and thrust was measured using a pendulum type thrust target. Experiments were performed with hydrogen, helium, and argon as propellant gas. Thrust increased with a discharge current up to 6kA and applied magnetic field up to 0.4T. Maximum thrust of 7N was obtained when the peak position of the applied magnetic field was set upstream of the muzzle of the MPDT. The highest thrust performance was obtained with hydrogen gas with divergent magnetic nozzle applied to the MPDT.

14:45

RR3 5 VASIMR VX-200 thruster throttling optimization from 30 to 200 kW JARED SQUIRE, CHRIS OLSEN, FRANKLIN CHANG-DIAZ, BENJAMIN LONGMIER, MAXWELL BALLENGER, MARK CARTER, TIM GLOVER, GREG MCCASKILL, *Ad Astra Rocket Company* The VASIMR® VX-200 experimental plasma thruster incorporates a 40 kW helicon plasma source with a 180 kW Ion Cyclotron Heating (ICH) acceleration stage integrated in a superconducting magnet. Argon propellant mass flow is injected up to 140 mg/s. Rapid plasma start up (<100 ms) and high pumping speed ($>10^5$ liters/s) in a 150 m^3 vacuum chamber achieve performance measurements with the charge exchange mean-free-path greater than 1 m in the background neutral gas (pressure $< 10^{-5}$ Torr). The thruster efficiency at 200 kW total power is $72 \pm 9\%$, the ratio of effective jet power to input RF power, with an Isp $= 4900 \pm 300$ seconds (flow velocity of 49 km/s), and an ion flux of $1.7 \pm 0.1 \times 10^{21}$/s. The thrust increases steadily with power to 5.8 ± 0.4 N until the power is maximized and there is no indication of saturation. The plasma density near the device exit exceeds 10^{18} m^{-3} with a power density over 5 MW/m^2. An extensive study of thruster performance, efficiency and thrust-to-power ratio, as a function of Ar propellant flow rate and ICH-to-helicon RF power ratio has been carried out over a total power range of 30 to 200 kW. Optimized throttling set points are determined. The experimental configuration and results of this study are presented.

SESSION RR4: MICRODISCHARGES III
Thursday Afternoon, 25 October 2012; Room: Salon DE at 13:30; Jichul Shin, University of Ulsan, presiding

Invited Papers

13:30

RR4 1 Modeling transient and DC microdischarges
LEANNE PITCHFORD, *LAPLACE, Univ Toulouse and CNRS*

The considerable recent interest in "microdischarges" (discharges in small, spatially-confined geometries) is largely due to their remarkable stability. That is, stable, non-thermal, high-pressure plasmas can be generated and maintained in electric discharges in small geometries operating in controlled atmospheres or in open air. Various ways of increasing the plasma volume have been investigated, including arrays of micro discharges or 3-electrode systems (an additional anode). Further interest in microdischarges is due to the fact that plasma jets, initiated from microdischarges operating with pulsed or RF excitation and with an axial helium flow, can propagate some centimeters in open air. Modeling has been an important tool for developing an understanding of these microdischarges and in helping guide the experimental optimization of devices based on microdischarges. This talk will focus on results from fluid modeling. Issues to be discussed include the extent to which pd (pressure x distance) and pt (pressure x time) scaling laws are valid for transient and DC microdischarges. That is, how do these microdischarges differ from their larger, lower-pressure counterparts? Nonlinearities due to gas heating, step-wise ionization, surface and high-pressure gas phase chemistry, and the high electric field strength at the cathode are factors that can cause departures from pd and pt scaling. Results from fluid models have also provided a framework for understanding of pulsed or rf plasma jets, but models allowing the prediction of the plasma chemistry in plasma jets are still evolving.

Contributed Papers

14:00

RR4 2 Properties of a field emission-driven Townsend discharge PAUL RUMBACH, DAVID GO, *University of Notre Dame* For half a century, it has been known that the onset of field emission in direct current (DC) microplasmas with gap sizes less than 10 μm can lead to breakdown at applied voltages far less than predicted by Paschen's law. It is still unclear how field emission affects other fundamental plasma properties at this scale. In this work, a one-dimensional fluid model is used to predict basic scaling laws for fundamental properties such as ion density, electric field due to space charge, and current voltage relations in the pre-breakdown regime. Computational results are compared with approximate analytic solutions. It is shown that ionizing collisions by field-emitted electrons produce significant ion densities well before Paschen's criteria for breakdown is met. When positive space charge densities become sufficiently large, the effect of ion-enhanced field emission leads to breakdown. Defining breakdown mathematically using a solvability condition leads to a full modified Paschen's curve, while defining it physically in terms of a critical ion density leads analytically to an effective secondary emission coefficient, γ', of the form initially suggested by Boyle and Kisliuk.*

*W. S. Boyle and P. Kisliuk, Phys. Rev. **97**, 255 (1955).

14:15

RR4 3 Stationary wave of microplasmas and its propagation in the array of microchannels JIN HOON CHO, PETER KIM, SUNG-JIN PARK, J. GARY EDEN, *Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign* Propagation of a stationary wave of microplasmas in an array of microchannels has been observed in rare gases at atmospheric pressure, and investigated spatiotemporally. The microchannels, fabricated in a spiral geometry, have widths of 200–300 μm, and a length-to-width aspect ratio of $\sim10^3$:1. The devices were powered with a 20 kHz sinusoid voltage and operated at 300–700 Torr in case of several rare gases. A gated, intensified camera and a telescope, with a frame resolution of ~50 ns reveal the formation of unique standing wave structures of microplasmas and the rapid propagation of the plasma structure radially outwards. The scale, spacing and propagation rate of the standing waves of microplasmas are dependent on the discharge gases, and the pressure. It is observed that the wave properties can be controlled by the device structure, and numerical analysis of the observed stationary waves along the azimuthal coordinate reveal a phase shift, oscillation and self-arrangement. The detailed characteristics of plasma wave propagation and these stationary waves will be discussed.

14:30

RR4 4 Plasma ignition dynamics in atmospheric-pressure pulsed-microwave plasma HIROTAKA TOYODA, TAKUYA MURASE, KAZUKI EGASHIRA, *Department of Electrical Eng., Computer Sci., Nagoya University* Atmospheric-pressure pulsed plasmas have been given much attention because of its various possibilities for industrial applications. In this study, temporal variations of both plasma density and microwave electric field in pulsed-microwave atmospheric-pressure plasma of Ar/H_2 and N_2/H_2 are measured using H_β line measurement. From time-resolved measurement of Ar/H_2 plasma from the plasma ignition till the steady state, both increase in plasma density and decrease in electric field are observed up to ~0.7 μs from the plasma ignition, and their relation is well explained by the decrease in the plasma resistivity and the current flowing through the plasma. After ~0.7 μs, plasma density starts to decrease rather slowly at a time scale of a few μs till it reaches the steady state. Time scale of the plasma density decrease is similar to that of the gas temperature increase, suggesting heat expansion of the neutral gas as well as the plasma in the vicinity of the plasma region.

SESSION SR1: PLASMA MODELING AND SIMULATIONS III

Thursday Afternoon, 25 October 2012; Room: Amphitheatre 204 at 15:30; Ikuo Sawada, Tokyo Electron Limited, presiding

Invited Papers

15:30

SR1 1 Kinetic and electromagnetic effects in technical plasmas
DENIS EREMIN, *Ruhr-Universität Bochum*

There is an accumulating body of evidence that kinetic effects play a significant role in practically all kinds of technical plasmas. Such plasmas often exhibit several groups of electrons with disparate energies, where electrons from different groups exchange energy only through weak processes. The intrinsically non-Maxwellian charachter of the electron distribution function in this case invalidates the fluid-based approaches for description of the technical plasmas. Rather, a self-consistent kinetic treatment is frequently needed for capturing all the important physics features, whereas fluid models under such conditions can yield quantitatively or even qualitatively erroneous results. Despite this, the fluid-based numerical codes remain a popular tool for investigation of the technical plasmas due to the low computational cost of such codes compared to that of the kinetic ones. The proper description of technical plasmas becomes further complicated if in addition to the kinetic treatment one needs to consider electromagnetic effects, which gain in significance as the electrode size and driving frequency increase, which continues to be the tendency in many CCP industrial plasmas usually described under the electrostatic approximation. In this talk we discuss modern techniques of parallelization of self-consistent kinetic particle-in-cell/Monte-Carlo (PIC/MCC) numerical codes on graphics cards (GPUs), which make kinetic simulations a routine numerical tool for investigation of technical plasmas. Then, we will demonstrate for the plasmas spanning broad parameter range examples of simulations made with such codes, where kinetic effects are important and thus the fluid description is inadequate. Finally, we argue that in many situations the electromagnetic effects relevant to the technical plasmas can be described in the framework of Darwin (magneto-inductive) approximation, which can be implemented as a natural modification in an electrostatic PIC/MCC code, as all the field equations are elliptic. We give the examples of kinetic simulations with electromagnetic effects obtained with such Darwin code.

Contributed Papers

16:00

SR1 2 Thermal mechanism of prepeak formation in Pulsed Glow Discharge MAXIM VORONOV, VOLKER HOFFMANN, *Leibniz Institute for Solid State and Materials Research (IFW) Dresden, Germany* TOBIAS STEINGROBE, WOLFGANG BUSCHER, CARSTEN ENGELHARD, *University of Münster, Institute of Inorganic and Analytical Chemistry, Germany* ANDREW STOREY, STEVEN RAY, GARY HIEFTJE, *Indiana University, Department of Chemistry, USA* NIMESA COLLABORATION* A microsecond Pulsed Glow Discharge (μs PGD) in a Grimm-type source is characterized by the so-called "prepeak," which is a spike in both electrical current and emission intensity at the leading edge of the discharge pulse. The prepeak is followed by synchronized vibrations of the current and the emission. To understand the nature of these phenomena, a microphone was inserted into the discharge chamber. Acoustical waves were detected and found to be in correlation with the measured vibrations. This points to a thermal mechanism for prepeak formation: the gas is heated in the leading edge of the discharge pulse and then expanded. To prove this suggestion, a Monte-Carlo based model was developed to simulate the evolution of Ar concentration, temperature, and flow in time and space. Potentially, the model could be used for gas simulations in a wide range of different applications. Here, the model is incorporated into an existing but modified model of the μs PGD in a Grimm-type plasma excitation source. Results of the simulations confirm that the thermal mechanism is responsible for the formation of the electrical prepeak and the pressure waves.

*International Collaboration in Chemistry: Novel Instumentation for Modern Elemental Speciation Analysis.

16:15

SR1 3 3D Hydrodynamic Simulations of Atmospherc-Pressure Inductively-Coupled Plasma Torches and Microwave Plasma Torches PETER WILLIAMS, *Agilent Technologies* We have performed fully 3D hydrodynamic simulations of atmospheric-pressure inductively coupled plasma (ICP) torches and microwave plasma (MP) torches. These simulations closely mirror the plasma conditions in ICP and MP torches designed for elemental analysis in commercial ICP-MS and MP-OES systems. Towards the goal of understanding transport in our torches, we show when and where we believe these torches may have turbulent flow. Our goal is to understand and hopefully reduce such turbulence as it is thought to lead to reduced instrumental sensitivity. Previous literature that investigated turbulence in ICPs via simulation has largely done so using 2D hydrodynamic simulations coupled with turbulence models such as k-epsilon. The advantage of this approach is an enormous savings in computational cost. The disadvantage is that models are only rough approximate representations of reality, and may give misleading results in some cases. Swirling flows in particular, such as exist in virtually all commercial ICP torches, present notoriously difficult problems for most turbulence models. It is for this reason that we have attempted to capture the turbulent breakdown directly. This requires high-resolution 3D simulations, which we have performed using the commercial package CFD-ACE.

16:30

SR1 4 Simulations of pulsed rf plasma sources using CFD-ACE+ MUSTAFA MEGAHED, ANANTH BHOJ, *ESI Group* SING KI NAM, RAJ DHINDSA, *Lam Research Corporation* ESI GROUP TEAM, LAM RESEARCH CORPORATION TEAM Pulsing techniques are increasingly being used in plasma processing reactors for newer technological nodes. Pulsed rf sources allow for additional "knobs" to control plasma parameters. In particular, varying the pulsing frequency, duty cycle and pulse shape enables manipulation of the fluxes and energy distribution functions. Accurate numerical simulations of pulsed discharges require that transients are tracked. Time scales for the rf signals, pulsing frequency and the neutral / heavy species response times can span orders of magnitude posing a significant challenge. The multi-physics modeling platform CFD-ACE+ was used in this work to address simulations of an Ar discharge in a typical CCP reactor configuration. The effect of pulsing on plasma characteristics was investigated. Initial results comparing the continuous and pulsed rf operating modes will be discussed.

16:45

SR1 5 Links between vortex formation and ambipolar flow in 2D ICP fluid simulations* DAVID URRABAZO, MATTHEW GOECKNER, *University of Texas at Dallas* Recent results by Bogdanov *et al.*, have suggested the presence of vortices within discharges. They have reported that these are related to a gradient in the electron temperature. We have also examined these vortices via fluid simulation of an ICP discharge developed with COMSOL 3.5a and Matlab. We will show via an examination of the curl of the electron flux that the source of the vortices is more complex then what was reported by Bogdanov *et al.*, Specifically, we will show that the source of is via several channels - often tied to the electron temperature profile but not necessarily directly related to the profile. Further, as the components related to these vortices are removed, the classic fluid model is reduced to the ambipolar model. This suggests that there are other ways to envision the ambipolar model outside of the requirement for flux congruence.

*Verity Instruments and National Science Foundation.

SESSION SR2: PLASMA ETCHING II

Thursday Afternoon, 25 October 2012; Room: Classroom 203 at 15:30; Ankur Agarwall, Applied Materials Inc., presiding

Invited Papers

15:30

SR2 1 Physics and chemistry of complex oxide etching and redeposition control

JOËLLE MARGOT,* *Physics department, Université de Montréal*

Since its introduction in the 1970s, plasma etching has become the universal method for fine-line pattern transfer onto thin films and is anticipated to remain so in foreseeable future. Despite many success stories, plasma etching processes fail to meet the needs for several of the newest materials involved in advanced devices for photonic, electronic and RF applications like ferroelectrics, electro-optic materials, high-k dielectrics, giant magnetoresistance materials and unconventional conductors. In this context, the work achieved over the last decade on the etching of multicomponent oxides thin films such as barium strontium titanate (BST), strontium titanate (STO) and niobate of calcium and barium (CBN) will be reviewed. These materials present a low reactivity with usual etching gases such as fluorinated and chlorinated gases, their etching is mainly governed by ion sputtering and reactive gases sometimes interact with surface materials to form compounds that inhibit etching. The etching of platinum will also be presented as an example of unconventional conductor materials for which severe redeposition limits the achievable etching quality. Finally, it will be shown how simulation can help to understand the etching mechanisms and to define avenues for higher quality patterning.

*In collaboration with MOHAMED CHAKER, INRS-Energie, Matériaux et Télécommunications.

Contributed Papers

16:00

SR2 2 A complete simulation of InP etching by Cl2/N2/Ar plasma mixture* ROMAIN CHANSON, AHMED RHALLABI, MARIE CLAUDE FERNANDEZ, CHRISTOPHE CARDINAUD, *Institut des Materiaux (IMN) - University of Nantes* PLASMAS COUCHES MINCES TEAM Deep anisotropic plasma etching of InP is an indispensable tool for the fabrication of a large variety of integrated optical devices. In this context, a 2D Monte Carlo etching model of InP by a Cl2/Ar/N2 plasma discharge coupled to a global kinetic plasma model and a sheath model have been developed. It allows the prediction of the geometrical and chemical profile of trenches etched through the mask versus the operating conditions. The plasma kinetic model is performed to quantify the reactive species densities and fluxes such as those of Cl, N and positive ions. The latter are introduced as the input parameters in the etching model. Under Cl2/Ar plasma mixture, the mechanism of the development of bowing defect is mainly attributed to the chemical etching of the adsorbed sites InClx. The impact of nitrogen addition into the Cl2/Ar gas mixture is studied. Both the simulations and the experiments show the role of the nitrogen on the disappearance of the bowing defect. This is attributed to the passivated layer due to the formation of InClxNy species. For a moderate nitrogen proportion, the passivated layer is mainly composed of InNCl2 and InNCl sites at the top of the InP etched trenches while at the bottom, the passivated layer is mainly composed by InN sites.

*This work is supported by French researcher agency (ANR) under INCLINE project.

Invited Papers

16:15

SR2 3 Plasma induced UV/VUV damage during Si and GaN device fabrication
TETSUYA TATSUMI, *Sony Corporation*

Plasma induced damages (PID) on semiconductor devices have been widely reported. Materials and the interface between stacked materials can be degraded by ions and photons during plasma processes. In this report, I focus on the effect of ultraviolet (UV) and vacuum ultraviolet (VUV) radiation on various devices. In the fabrication of Si-CMOS devices, high-density plasmas are used for dry etching. The light from plasma is absorbed by the materials when its energy is greater than the band gap (Eg). For example, the Eg of the gate SiO2 is about 8.8 eV; consequently the plasma emissions with wavelengths lower than 150 nm are absorbed by SiO2. These VUV lights degrade the surface structure of SiO2 and increase its wet etch rate [1]. SiOCH and ArF photo resist have been used to realize high-speed devices with low power consumption. These materials have a very weak bond, so there are sometimes problems such as increased dielectric constant in SiOCH or a roughening or wiggling of ArF resist caused by UV/VUV [2]. Plasma emission can also affect the electrical and/or optical properties of devices. I investigated the effect of radiation on the interface-trap density (D_{it}) of a SiN/Si structure [3]. When photons in the UV region (200–300 nm) were irradiated, the D_{it} increased and a negative charge was generated in the interface. This indicates that VUV/UV radiation transmitting through the upper dielectrics causes the electrical characteristics of underlying devices to fluctuate. GaN-based semiconductors are used for optoelectronic device applications, so I also investigated the PID of a GaN/InGaN/GaN stacked structure. The samples were exposed to Cl2 plasma emission and analyzed by using photoluminescence (PL). PL intensity decreased when the plasma emission was irradiated. UV radiation (<360 nm) affects damage formation at the InGaN active layer [4]. Monitoring VUV/UV and understanding its effect on surface eactions, film damage, and electrical and/or optical performance are indispensable to fabricate advanced devices.

[1] T. Tatsumi *et al.*, Jpn. J. Appl. Phys. **33**, 2175 (1994).
[2] S. Uchida *et al.*, J. Appl. Phys. **103**, 073303 (2008).
[3] M. Fukasawa *et al.*, Jpn. J. Appl. Phys. **51**, 026201 (2012).
[4] M. Minami *et al.*, Jpn. J. Appl Phys **50**, 08JE03 (2011).

Contributed Papers

16:45

SR2 4 Role of Photons, Ion Implantation and Mixing in Sub-threshold Selective Etching of Si JULINE SHOEB, SARAVANAPRIYAN SRIRAMAN, TOM KAMP, ALEX PATERSON, *Lam Research Corporation, Fremont, CA* ETCH PRODUCT DEVELOPMENT, LAM RESEARCH CORPORATION, FREMONT, CA TEAM As device sizes shrink, control of selectivity and damage during plasma etching becomes important. Recent literature reports the role of photons in the cleaving of surface and sub-surface Si-Si bonds which may initiate Si etching by radicals, even below the threshold energies needed for ion-assisted etch.* Simultaneous effects of photons and ion penetration can degrade the selectivity. Photon assisted Si etching in below-threshold ion energies in Cl_2 plasmas reported 4-10 nm/Min. etch rate.† We investigated the effects of photons in sub-threshold etching of Si in $HBr/He/O_2$ plasmas. As photons with wavelengths <170 nm have enough energy to cleave Si-Si bonds, we concentrated on 58.4 nm photons emitting from He($2\,^1p$) and 130nm photons emitted by O(3s) which can penetrate ~10 nm intoe Si.[‡] This paper will discuss the role of photons and mixing in silicon-dioxide/silicon etching using modeling & simulation, experiments and diagnostics.

*H. Shin, W. Zhu, V. M. Donnelly, and D. J. Economou, J. Vac. Sci. Technol. A **30**(2), 021306 (2012).
†Ibid.
‡J. R. Woodworth, M. E. Riley, V. A. Amatucci, T. W. Hamilton, and B. P. Aragon, J. Vac. Sci. Technol. A **19**, 45 (2001).

17:00
SR2 5 Plasma damage and restoration of a spin-on organic ultra low-k material (k = 2.3) MIKOLAJ LUKASZEWICZ, *Wroclaw University* JEAN-FRANCOIS DE MARNEFFE, CHRISTOPHER J. WILSON, LIPING ZHANG, HSIN-YING PENG, PATRICK VERDONCK, MIKHAIL BAKLANOV, *Imec v.z.w.* As interconnect dielectrics, spin-on polymers might offer some advantages over OSG materials. In particular, a lower k-value is possible with less porosity, smaller pore size. They also have greater resistance to plasma damage due to their mono-component nature. However, some chemical modifications during the plasma exposure cannot be avoided. In this work, we study the changes caused by a N_2-H_2-C_2H_4 CCP discharge used for damascene patterning, on a spin-on k = 2.3 organic low-k material. It is shown that this plasma forms amine and ester groups, leading to hydrophilization and k-value degradation. Several restoration treatments are studied on blanket wafers, trying to restore the chemical composition, minimize the k-value and hydrophilization. Those treatments include exposure to in-situ He-H_2 discharge, high temperature He-H_2 afterglow and combinations thereof, low- and high-temperature VUV treatments. It is found that the best k-value gain is around 50%, and the most promising repair treatment results from the short exposure to a combination of low temperature in-situ He-H_2 discharge and high temperature He-H_2 afterglow. Applying such restoration process to an array of 30nm trenches, the integrated k-value showed a gain of 13% in RC constant, indicating efficient restoration to pristine k-value, although the chemical composition was not completely restored in all evaluated conditions.

17:15
SR2 6 Controlling Ion and UV/VUV Photon Fluxes in Pulsed Low Pressure Plasmas for Materials Processing* PENG TIAN, MARK J. KUSHNER, *University of Michigan* UV/VUV photon fluxes in plasma materials processing have a variety of effects ranging from damaging to synergistic. To optimize these processes, it is desirable to have separate control over the fluxes of ions and photons, or at least be able to control their relative fluxes or overlap in time. Pulsed plasmas may provide such control as the rates at which ion and photon fluxes respond to the pulse power deposition are different. Results from a computational investigation of pulsed plasmas will be discussed to determine methods to control the ratio of ion to photon fluxes. Simulations were performed using a 2-dimensional plasma hydrodynamics model which addresses radiation transport using a Monte Carlo Simulation. Radiation transport is frequency resolved using partial-frequency-redistribution algorithms. Results for low pressure (10s of mTorr) inductively and capacitively coupled plasmas in Ar/Cl_2 mixtures will be discussed while varying duty cycle, reactor geometry, gas mixture and pressure. We found that the time averaged ratio of VUV photon-to-ion fluxes in ICPs can be controlled with duty cycle of the pulsed power. Even with radiation trapping, photon fluxes tend to follow the power pulse whereas due to their finite response times, fluxes of ions tend to average the power pulse. Due to the overshoot in electron temperature that occurs at the start of low-duty-cycle pulses, disproportionately large photon fluxes (compared to ion fluxes) can be generated.

*Work supported by DOE Office of Fusion Energy Science, Agilent Labs and Semiconductor Res. Corp.

SESSION SR3: ELECTRON COLLISIONS WITH ATOMS AND MOLECULES
Thursday Afternoon, 25 October 2012; Room: Classroom 202 at 15:30; Klaus Bartschat, Drake University, presiding

Invited Papers

15:30
SR3 1 Low-energy electron interactions with water and methanol
LEIGH HARGREAVES, *California State University Fullerton*

Interactions of electrons with small, highly polar molecules form a crucial basis for understanding cellular damage caused during radiation therapy of cancers. Recent studies of elastic scattering from water by Khakoo *et al.* [1], and electronically inelastic scattering by Thorn *et al.* [2], have revealed serious discrepancies between experimental and theoretical determinations of the cross sections for these processes, and in some cases even between experimental values. In this presentation, new data for both elastic and electronic excitation of water are presented which aim to resolve some of these discrepancies. We will also consider excitation cross sections for a more complicated target, methanol. The measured methanol data are the first such data reported.

[1]M. A. Khakoo *et al.*, Phys. Rev. A **78**, 052710 (2010).
[2]P. A. Thorn *et al.*, J. Phys. B: At. Mol. Phys. **40**, 697 (2007).

Contributed Papers

16:00
SR3 2 Electron Collision Processes with Carbon Dioxide: Resolving Long-Standing Paradoxes* T.N. RESCIGNO, D.J. HAXTON, *LBNL* C.W. MCCURDY, *LBNL and UC Davis* The principal features of low-energy electron-CO_2 collisions have been known and studied for over forty years. The scattering is characterized by a rapid rise in the total cross section below 1 eV, anomalous threshold behavior for excitation of symmetric stretch and bending vibrational modes, resonant vibrational excitation near 4 eV with weak "boomerang" structure in the excitation cross sections

and dissociative electron attachment cross sections leading to CO + O^- which peak near 4 eV and 8 eV and have angular distributions which show large deviations from axial recoil. The nuclear dynamics associated with all these features is intrinsically polyatomic in nature and cannot be described with one-dimensional models. The present study provides a consistent description of all these phenomena and resolves a number long-standing paradoxes and misconceptions found in the extant literature.

*Work supported by USDOE, Office of Basic Energy Sciences, Division of Chemical Sciences.

16:15

SR3 3 Accuracy of OAMO (Orientation Averaged Molecular Orbital) approximation for calculating electron-impact ionization cross sections for molecules* ADAM UPSHAW, BEN PAYNE, *Missouri S&T* JAMES COLGAN, *Los ALamos National Lab.* DON MADISON, *Missouri S&T* We have been using the M3DW (molecular 3-body distorted wave) approximation plus the OAMO (orientation averaged molecular orbital) to calculate cross sections for electron-impact ionization of molecules. The approximation yielded good agreement with experiment for H2 and reasonable agreement for N2. However, the agreement was not that good for H2O, CH4, and larger molecules so the important question concerns if the disagreement is a result of the OAMO approximation or a problem with the theoretical approach. Consequently we have modified our computer codes to perform a proper average over molecular orientations. M3DW results both with and without making the OAMO approximation will be compared with experimental measurements.

*Work supported by the NSF.

Invited Papers

16:30

SR3 4 Cross Sections for Electron-impact Excitation of Electronic States in Atoms and Molecules - Application Examples of the BE*f*-scaling model in Optically-allowed Transitions

HIDETOSHI KATO, *National Institute of Advanced Industrial Science and Technology (AIST)*

The differential cross section (DCS) and integral cross section (ICS) measurements of electron-impact electronic excitation for noble gases were reported by many groups. Unfortunately, despite all these endeavours, if we were to characterize the level of agreement between these studies, then we could only conclude that it remains "patchy" at best. Hence, we report measurements of DCS and ICS for electron-impact excitation of the lowest electronic states in noble gases (Ne, Ar, Kr and Xe), and compare with results from a scaled Born cross section (BEf-scaling). We have previously found for the He atom and a number of molecules, including H_2, O_2, CO, H_2O, CO_2, N_2O and C_6H_6 that the BEf-scaling approach, for calculating ICSs for dipole-allowed electronic-state transitions, can lead to a very accurate description of the various scattering processes from threshold to 2000 eV [1]. Exceptions to this general statement have only been found in those cases where resonance effects due to the temporary capture of the incident electron by the target and contamination from an accidentally degenerate or near-degenerate triplet state have arisen. Our results for noble gases will be presented in detail at the conference.

[1]H. Kato *et al.*, NIFS Research Report, NIFS-DATA-108, 1 (2009).

Contributed Papers

17:00

SR3 5 Relativistic convergent close-coupling calculation of the spin polarization of electrons scattered elastically from zinc and mercury* CHRISTOPHER BOSTOCK, DMITRY FURSA, IGOR BRAY, *Curtin University* We present spin asymmetry parameters (Sherman functions) for elastic electron scattering on zinc and mercury atoms calculated using the relativistic convergent close-coupling (RCCC) method. The Zn and Hg atoms are each modeled as two active electrons above a Dirac-Fock core. Three key features of the RCCC method are critical: (1) an em ab initio treatment of spin via the Dirac equation, (2) a unitary treatment of the scattering process, and (3) correct antisymmetrization of the total wave function. There is excellent agreement between the RCCC results and experiment for the case of Hg across a wide range of energies, and similarly there is excellent agreement between RCCC results and experiment for Zn across the range of energies where $3d^{10}$ core excitation levels do not appear. The results are relevant in light of the recent controversial claim by Williams *et al.* [Phys. Rev. A 85, 022701 (2011)] that relativistic scattering theories do not account for spin properly during electron scattering on quasi two-electron targets such as Zn and Hg; the claim is made that a geometric "Berry" phase is required to augment fundamental scattering theories.

*Supported by the Australian Research Council.

17:15

SR3 6 Quantum Control of Diatomic Molecular Vibration States Using Space-Time Discretization* CHARLES WEATHERFORD, XINGJUN ZHANG, *Physics Department, Florida A&M University* Molecular evolution in an external field can be efficiently calculated by using our Space-Time algorithm (STA), which deploys a basis set in space and time and turns Quantum Mechanical initial-value problems into a set of simultaneous algebraic equations and can be used to simulate the control of the Quantum states of a molecule. The external field must be optimized so as to restrict the search space to those parameter values characterizing the field, which are available in experiments. A generalized evolution strategy is employed which provides a technique for parameter optimizations. We have developed a parallel algorithm which implements an evolution strategy using the STA to optimize the external field intensity (laser amplitude) so as to drive the molecule from an initial vibrational state to a desired vibrational state. We optimize the molecular evolution procedure in two ways: a step-by-step optimization and a closed-loop optimization. The method is applied to NO^+. The simulation has been done using 5 vibrational states.

*Supported by the US Army and the National Science Foundation cooperative agreement 0630370 (CREST).

SESSION SR4: PLASMAS IN LIQUIDS
Thursday Afternoon, 25 October 2012
Room: Salon DE at 15:30
Natalia Babaeva, University of Michigan, presiding

Contributed Papers

15:30

SR4 1 Controlling Cold Plasma Jets Interacting with Liquids* STEPHAN REUTER, MALTE HAMMER, JOERN WINTER, KAI MASUR, *plasmatis at INP Greifswald e.V.* THOMAS VON WOEDTKE, KLAUS-DIETER WELTMANN, *INP Greifswald e.V.* Plasmas interacting with liquids are of great interest for environmental, chemical, and biomedical applications. In this work we present optical diagnostics on atmospheric pressure plasma jets interacting with liquids. Combining the diagnostic results with numerical simulations yields an understanding of fundamental processes such as air species diffusion into the jet effluents. Especially for plasma treatment of physiological liquids in ambient air, atmospheric species play a key role. To achieve a desired reactive component output, the generation processes from these ambient air species are controlled. Plasma jets are characterized by laser induced fluorescence spectroscopy, by absorption and emission spectroscopy, and by flow simulations. With the gained knowledge we are able to tailor the reactive component composition and to influence plasma jet-liquid interaction. We show that reactive species generation within plasma treated liquid can be tuned and apply the findings to biological cells to investigate the effect of reactive oxygen and nitrogen species (RONS). The plasma treated liquids are investigated regarding their pH value, OH radicals, nitrate and nitrite, and H_2O_2 content. From the tailored plasma treatment a significant insight into the relevant processes in plasma acidification of liquids has been gained.

*funded by the German Federal Ministry of Education and Research.

15:45

SR4 2 Time-resolved measurement of pressure evolution in underwater nanosecond discharge ILYA MARINOV, OLIVIER GUAITELLA, SVETLANA STARIKOVSKAIA, ANTOINE ROUSSEAU, *LPP, Ecole Polytechnique* COLD PLASMA TEAM Electrical discharges in water and other dielectric liquids have been extensively studied since almost fifty years, however reliable data on plasma parameters within the propagation phase is still missing. We report on shadowgraphic imaging and optical emission spectroscopy (OES) both with nanosecond time resolution of pulsed nanosecond discharge generated with point to wire electrode configuration. High voltage pulses of 10 kV and 30 ns duration (FWHM) are delivered by commercial pulse generator FPG 10 (FIG GmbH). Sub-millimeter discharge with filamentary structure develops at 50 km/s in axial direction of pin electrode. Using Hugoniot equations maximal discharge pressure at ignition can be obtained from shock wave front velocity. Analytical model of supersonic cavity expansion based on Kirkwood-Bethe approximation gives discharge pressure evolution from experimentally measured discharge channel expansion velocity profile. Thus, the pressure of 5 GPa is measured at the discharge ignition and drops drastically by the end of voltage pulse. Time-resolved OES spectrum shows a strong broadening of atomic Hydrogen (Balmer series) and oxygen (OI 777 nm) lines with almost continuum emission in the region 300–700 nm. Complex Hα and OI 777 profiles are due to combined contribution of Van Der Waals and Stark broadening. Electronic density can be deduced from lorentzian fit of Stark broadening and gives for electronic density $10^{24}-10^{25}$ m^{-3}.

16:00

SR4 3 Simulations of Images and Optical Spectra of Plasmas Sustained in Bubbles in Water* WEI TIAN, MARK KUSHNER, *University of Michigan* Plasmas in bubbles in water are being investigated for their ability to produce chemically reactive species for water purification and medical treatment. The gas in the bubbles is important to the production of these active species. In this paper, we report on a computational investigation of the dynamics of plasmas in bubbles in water. These simulations were performed using *nonPDPSIM*, in which Poisson's equation, transport equations for charged and neutral species, and electron temperature are integrated in 2-dimensions on an unstructured mesh. Bubbles of specified composition and size ($\approx$3 mm diameter) in water at atmospheric pressure are placed at the tip of the powered electrode and water vapor is allowed to diffuse into the bubble from the vapor-water boundary. Voltage pulses (15–30 kV) produce plasma streamers in the bubble which typically hug the vapor-water boundary. Images, optical spectra and plasma properties will be discussed for bubbles of N_2, Ar and He, and compared to experiments [1]. The differences in plasma dynamics and appearance (e.g., volume discharge or surface hugging) depend in large part on the electron energy relaxation length, and the rate of diffusion of water vapor into the interior. Electron impact dissociative excitation of water vapor and excitation transfer processes from injected bubble gases to the water vapor are responsible for differences in the optical spectra and, by inference, differences in radical production.

*Work supported by the DOE Office of Fusion Energy Sciences.

[1]K. Tachibana *et al.*, Plasma Sources Sci. Technol. **20**, 034005 (2011).

16:15

SR4 4 An efficient method for producing standing sonoplasmas with the help of a metal mesh K. SASAKI, Y. IWATA, S. TOMIOKA, S. NISHIYAMA, *Hokkaido University* N. TAKADA, *Nagoya University* It is known that sonoplasmas are produced at the collapses of cavitation bubbles in liquids irradiated by ultrasonic waves. Sonoplasmas are probably produced in commercialized ultrasonic cleaners, but it is very difficult to detect optical emission from sonoplasmas in ultrasonic cleaners. In this work, we found an efficient, simple method for producing sonoplasmas. We prepared a rectangular container that was filled with water. An ultrasonic transducer was attached at the bottom of the container, and ultrasonic wave at a frequency of 34 kHz was propagated in water from the bottom toward the top. When we inserted a planar metal mesh into water from the top, we observed the efficient production of cavitation bubbles at a localized distance from the mesh. The production area of the cavitation bubbles was roughly standing. It was necessary to adjust the depth of water and the position of the mesh carefully to obtain the efficient production of standing cavitation bubbles. We adopted laser light scattering as a simple method for quantifying the production efficiency of cavitation bubbles, and optimized the depth of water and the position of the mesh. We succeeded in capturing the optical emission image of a sonoplasma using a charge-coupled device camera with an image intensifier.

16:30

SR4 5 Optical emission spectroscopy and shadowgraph imaging of pulsed laser plasmas generated in gaseous, liquid and supercritical CO_2* TORU KATO, YOSHIHIKO TAKIZAWA, SVEN STAUSS, MOTOYOSHI BABA, TOHRU SUEMOTO, KAZUO TERASHIMA, *The University of Tokyo* Pulsed laser ablation (PLA) in liquids has attracted a lot of attention due to its potential for the synthesis of a wide range of nanomaterials. Contrary to PLA in vacuum, in liquids the plasma plume is confined due to the high density of the medium. This restricts the diffusion of active species and leads to rapid quenching, which limits particle growth. Compared to liquids, supercritical fluids (SCFs) possess superior transport properties and PLA in SCFs has been used for realizing chemical synthesis of nanomaterials such as diamondoids. We have investigated the dynamics of PLA (laser: Nd-YAG, wavelength 532 nm; pulse width 7 ns; frequency 10 Hz; target: carbon, nickel) in gaseous (0.1-6 MPa), liquid and supercritical CO_2 (T_{crit}: 304.1 K, P_{crit}: 7.38 MPa). From shadowgraphs of PLA taken in gaseous, liquid and supercritical CO_2, images of PLA in SCF showed characteristics similar to that of PLA in liquid. Compared to PLA in the gaseous and liquid states, optical emission spectra in SCF revealed enhanced interactions between plasma and solvent species, especially near the critical point. Owing to the high density fluctuation near the critical point, PLA in SCF is expected to lead to a better control of the synthesis of diamondoids and other nanomaterials.

*This work was supported financially in part by a Grant-in-Aid for Scientific Research on Innovative Areas (Grant No. 21110002) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

16:45

SR4 6 Experimental and Modeling Analysis of the Single Micro Bubble Generation by Micro Plasma in Water* PENG XIAO, DAVID STAACK, *Mechanical Engineering Department, Texas A&M University* PLASMA ENGINEERING AND DIAGNOSTIC LABORATORY TEAM A single micro bubble (maximum diameter 50 to 600 μm) is shown to be formed by a single nanosecond duration micro plasma in liquid. The micro scale corona plasma discharges are created at the tip of a micro-electrode with high energy density. Discharge conditions are controllable with tip diameter 1um, applied voltage 5 kV to 10 kV, discharge duration 10 ns to 1 μs and discharge energy 1 mJ to 50 mJ per pulse. The energy input from the micro plasma to generate the micro bubble and to support its growth vary, which leads to variations in the rate of growth, maximum diameter, and the number of growth-collapse cycles of the micro bubble. These micro plasma based micro bubbles are visualized using a microscope based shadow graph system and two high speed cameras. The micro plasma discharge is captured with nanosecond gating using an ICCD and the micro bubble generation and growth is recorded using million fps CCD video camera. The micro bubbles are found repeatedly generated. A Payleigh-Plesset model for growth and collapse of cavity bubble are compared to micro bubble videos and used to estimate the time dependent pressure, temperature and mass of the micro bubbles.

*Funded by NSF grant PHY-1057175.

17:00

SR4 7 Microsparks Generated by Charged Particles in Dielectric Liquids ROBERT GEIGER, *Texas A&M University* DAVID STAACK TEAM The electrodynamics of charged particles in dielectric liquids have been described by several authors [1,2]. As a charged particle approaches an electrode of opposite charge the local electric field eventually exceeds the dielectric strength of the liquid and a microspark is generated. These plasmas can be very small, about < 5 μm, and may exhibit non-thermal behavior. Such non-thermal behavior can provide interesting and efficient chemical reactions [3]. An understanding of the plasma properties for this type of discharge can provide a simple means of generating non-thermal plasmas in dielectric liquids, such as oils or other hydrocarbons, which can be used to chemically process the liquids. Such a technology may lead to a highly efficient method of heavy oil upgrading which can be easily scaled. In order to understand the plasma properties optical emission spectroscopy is carried out for various hydrocarbons and voltage-current characteristics are used to determine the energy cost for this process.

[1] Melcher, James R., Continuum Electromechanics. Cambridge, MA: MIT Press, 1981.
[2] Jones, Thomas B. Electromechanics of Particles. Cambridge University Press 1995.
[3] D. Staack, A. Fridman, A. Gutsol, Y. Gogotsi, and G. Friedman, Angew. Chem., Int. Ed. **47**, 8020 (2008).

17:15

SR4 8 Pulse discharge in the focus of the converging acoustic wave in the water VALERIY CHERNYAK, SERGIJ SIDORUK, VITALIJ YUKHYMENKO, EVGEN MARTYSH, *Kyiv National Taras Shevchenko University* OLEG FEDOROVICH, *Institute of Nuclear Research, National Academy of Sciences of Ukraine* KYIV NATIONAL TARAS SHEVCHENKO UNIVERSITY TEAM, INSTITUTE OF NUCLEAR RESEARCH, NATIONAL ACADEMY OF SCIENCES OF UKRAINE TEAM Generation of the acoustic signals made by the two successive microsecond's discharges in the liquid system of cylindrical geometry was investigated. The ratio of the radius of stainless steel cylinder to its height is ~13.5. Both discharges are realized between two electrodes placed on the cylinder axis. The ratio of the cylinder height to the distance between electrodes is ~3. Controlled time delay between discharges was changed in the wide range: from the moment when the first divergent acoustic wave (generated by the first discharge in the water) reaches the metal wall of cylinder till the time after the axial collapse of the converging acoustic wave (reflected from the cylinder wall). The energy in storage capacitors was changing in the range of 1÷1000 joules. The air discharger and hydrogen thyratron were used as commutators for the first and the second discharges correspondingly.

SESSION UF1: BIOLOGICAL AND BIOMEDICAL APPLICATIONS OF PLASMAS II
Friday Morning, 26 October 2012
Room: Classroom 107 at 9:00
Bill Graham, Queen's University Belfast, presiding

Contributed Papers

9:00

UF1 1 Generation and characteristic survey of atmospheric-pressure dry, vapor, mist plasma jet using high-frequency high-voltage power supply* NORIMITSU TAKAMURA, *Graduate School of Science and Technology, Kumamoto University* DOUYAN WANG, *Priority Organization for Innovation and Excellence, Kumamoto University* TAKAO NAMIHIRA, *Bioelectrics Research Center, Kumamoto University* HIDENORI AKIYAMA, *Graduate School of Science and Technology, Kumamoto University* Atmospheric-pressure plasma jet has attracted in the various fields for example surface treatment of materials, bacterial killing and so on. The reasons why the plasma used these applications are because it is a non-thermal, high pressure, uniform glow plasma discharge that produces a high velocity effluent stream of highly reactive chemical species. While passing through the plasma, the feed gas becomes excited, dissociated or ionized by electron impact. Once the gas exits, the discharge volume, ions and electrons are rapidly lost by recombination, but the fast-flowing effluent still contains neutral metastable species and radicals. In our previous study, GFP-7R proteins were promoted delivering into the HeLa cells by dry plasma jet. In this case, we irradiated dry plasma jet only the surface of cell suspension. Therefore, it may be expected that raising the ratio of surface area/volume exposed to plasma by to mist the cell suspension causes further improvement of protein transduction efficiency by irradiating plasma. In this study, we investigated the optimal driving parameters of the plasma jets. The length of dry, vapor, and mist plasma jets and the generated chemical species of each plasma jet will be introduced at the conference.

*This work was a part of the Global COE program on "Global Initiative Center for Pulsed Power Engineering" of Kumamoto University from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

9:15

UF1 2 Feed gas humidity introduced into a MHz atmospheric pressure argon plasma jet affects plasma-generated species and plasma-treated human skin cells* JÖRN WINTER, KRISTIAN WENDE, MALTE U. HAMMER, HELENA TRESP, SYLVAIN ISENI, MARIO DÜNNBIER, KAI MASUR, *ZIK plasmatis at the INP Greifswald e.V.* KLAUS-DIETER WELTMANN, *INP Greifswald* STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* It is known, that gas humidity is an important parameter in plasma treatment of biological systems under ambient conditions. However, humidity in the feed gas of an atmospheric pressure plasma jet is even more crucial than ambient humidity since humid working gas is transported through the active plasma zone and the water molecules become dissociated. The so produced oxygen/hydrogen species are significant for the active plasma component composition. In this work the effect of feed gas humidity on the plasma, on plasma-treated cell growth medium (RPMI) and subsequently on human skin cells is investigated. It is shown, that already small concentrations of humidity (<1000 ppm) induce changes in the optical emission spectrum of the effluent, increase H_2O_2 concentration in liquid cell growth medium and inhibit human skin cell proliferation.

*This work is founded by German Ministry of Education and Research (grant number: 03Z2DN12).

9:30

UF1 3 Modeling of inactivation of surface borne microorganisms occurring on seeds by cold atmospheric plasma (CAP) ANINDITA MITRA, Y.-F. LI, T. SHIMIZU, TOBIAS KLÄMPFL, J.L. ZIMMERMANN, G.E. MORFILL, *Max-Planck-Institute for Extraterrestrial Physics, Garching, 85741, Germany* Cold Atmospheric Plasma (CAP) is a fast, low cost, simple, easy to handle technology for biological application. Our group has developed a number of different CAP devices using the microwave technology and the surface micro discharge (SMD) technology. In this study, FlatPlaSter2.0 at different time intervals (0.5 to 5 min) is used for microbial inactivation. There is a continuous demand for deactivation of microorganisms associated with raw foods/seeds without loosing their properties. This research focuses on the kinetics of CAP induced microbial inactivation of naturally growing surface microorganisms on seeds. The data were assessed for log- linear and non-log-linear models for survivor curves as a function of time. The Weibull model showed the best fitting performance of the data. No shoulder and tail was observed. The models are focused in terms of the number of log cycles reduction rather than on classical D-values with statistical measurements. The viability of seeds was not affected for CAP treatment times up to 3 min with our device. The optimum result was observed at 1 min with increased percentage of germination from 60.83% to 89.16% compared to the control. This result suggests the advantage and promising role of CAP in food industry.

9:45

UF1 4 Influence of plasma-treatments on the structure, superstructure, and function of membrane lipids* MALTE U. HAMMER, ENRICO FORBRIG, *ZIK plasmatis at the INP Greifswald e.V.* KLAUS-DIETER WELTMANN, *INP Greifswald e.V.* STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* Every cell, eu- or prokaryotic, has a membrane as an interface to the environment. Every substance that is applied from outside the cell has to interact with it. This includes plasma-generated reactive species in the liquid cell environment created by plasma-treatment. By the Singer and Nicolson model, proteins are embedded in a lipid bilayer. Proteins are the functional elements, lipids are the structural elements. Due to the amphiphilic nature of the lipids, they form (super-) structures in an aqueous environment. The exact superstructure is determined by a structural parameter of the lipid, its shape. Here, we show experiments on lipids by fluorophore-based liposome assays and raman spectroscopy. The results show a membrane-activity of plasma-born reactive species against lipids and lipid structures. Based on this results and literature, we propose a model for a lesion-forming mechanism in membranes of some reactive species created by plasma-treatment. It is based on a hydrophobic-hydrophilic mismatch due to lipid peroxidization induced by reactive species generated in liquids by plasma-treatment.

*This work is founded by German Federal Ministry of Education an Research (grant# 03Z2DN12). Thanks to S. Hahn for great assistance.

10:00

UF1 5 Effect of Plasma Pretreatments on the Bio-adhesive Functionalized by Biomimetic Catechol Groups to Human Dentin SANGBAE LEE, KWANGMAHN KIM, KYOUNGNAM KIM, *Yonsei University* Plasma pretreatments have been introduced for modifying the surface chemistry of biomaterials. In an effort to improve the strength of the human dentin/bio-adhesive joint, oxygen plasma pretreatments to the bio-adhesive were investigated. Plasma treatments were carried out using custom-built and low pressure. Dentin were treated with plasma and used to prepare lap shear tests. Bio-adhesives were prepared synthesizing dopamine methacrylamide (DMA) monomer. DMA were copolymerized with 2-methoxyethylacrylate (MEA) by free radical polymerization. Proton nuclear magnetic resonance (^{1}H-NMR) and Gel permeation chromatography (GPC) analysis on samples of synthesized *p*(DMA-*co*-MEA) was performed to confirm that the resulting materials had the desired chemical structure. The effects of plasma pretreatments on surface chemistry were studied using Fourier transform infrared analysis (FTIR), and contact angle measurements. Oxygen plasma pretreatments enhanced adhesive strength by oxidizing of the catechol residue and creating a cross-linking as compared with control group. Furthermore plasma pretreatments lead to increase hydrophilicity of copolymers. Prospectively, the great potential of advanced technology in creation of the "Plasma pretreatment to the DOPA adhesives" would lead to the development of versatile method for coating to medial devices as well as dentin bonding.

10:15

UF1 6 Treatment of oral cancer cells with nonthermal atmospheric pressure plasma jet* JAMES YURKOVICH, XU HAN, BENJAMIN COFFEY, MATEJ KLAS, SYLWIA PTASINSKA, *University of Notre Dame* Non-thermal atmospheric pressure plasmas are specialized types of plasma that are proposed as a new agent to induce death in cancer cells. The experimental phase of this study will test the application of such plasma to SCC-25 oral cancer cells to determine if it is possible to induce apoptosis or necrosis. Different sources are used on the cells to find a configuration which kills cancer cells but has no effect on normal cells. The sources have been developed based on the dielectric barrier discharge between two external electrodes surrounding a dielectric tube; such a configuration has been shown to induce breaks in DNA strands. Each configuration is characterized using an optical emission spectrophotometer and iCCD camera to determine the optimal conditions for inducing cell death. The cells are incubated after irradiation with plasma, and cell death is determined using microscopy imaging to identify antibody interaction within the cells. These studies are important for better understanding of plasma species interactions with cancer cells and mechanisms of DNA damage and at latter stage they will be useful for the development of advanced cancer therapy.

*This research was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Basic Energy Sciences, Office of Science, United States Department of Energy through grant number DE-FC02-04ER15533.

10:30

UF1 7 The influence of the air plasma jet on early adherent events of L929 fibroblasts on cell culture polystyrene plate JUNG-HWAN LEE, JAE-SUNG KWON, JI-YEON OM, *Department and Research Institute of Dental Biomaterials and Bioengineering, College of Dentistry, Yonsei University, Republic of Kore* YONG-HEE KIM, EUN-HA CHOI, *Plasma Bioscience Research Center, Kwangwoon University, Republic of Korea* KWANGMAHN KIM, KYOUNG-NAM KIM, *Department and Research Institute of Dental Biomaterials and Bioengineering, College of Dentistry, Yonsei University, Republic of Kore* Recently, atmospheric pressure plasma was applied to biological field. The aim of this study was to identify whether the air plasma jet increases fibroblast early attachment under moving motion on the cell culture polystyrene plate. Polystyrene plate was treated with plasma jet using compressed air. After 2 minutes of treatment, L929 was seeded on polystyrene plate as well as on untreated plate. Cells were allowed to attach for 4 hours under 70 RPM. FE-SEM, confocal microscopy and RT-PCR were used to evaluate characters of cells. The results suggested that plasma treatment on the polystyrene plate altered surface energy without change of roughness. In occasion of treatment plate, attached L292 were significantly found but not found on untreated surface. Also, despite the small area of treated center by the flame of the plasma jet, cells were also attached on round surface of the area covered by the flame, which suggests that the effect was not only due to the jet flame but perhaps due to the jet interacting with surrounding atmosphere. In the light of this study, the air plasma jet could be useful for early attachment of L292 on the polystyrene plate under moving motion and can be applied to biomaterials.

10:45

UF1 8 Effect of non-thermal atmospheric pressure plasma jet on human breast cancer cells SHAHRIAR MIRPOUR, *Laser-Plasma Research Institute, Shahid Beheshti University, Evin, 1983963113, Tehran, Iran* MARYAM NIKKHAH, SOMAYE PIROUZMAND, *Department of Nanobiotechnology, Faculty of Biological Sciences, Tarbiat Modares University, Tehran, Iran* HAMID REZA GHOMI, *Laser-Plasma Research Institute, Shahid Beheshti University, Evin, 1983963113, Tehran, Iran* Nowadays, Non-thermal plasma enjoy a wide range of applications in biomedical fields such as Sterilization, Wound healing, Cancer treatment and *etc*. The aim of this paper is to study the effect of non-thermal atmospheric pressure plasma jet on breast cancer (MCF-7) cells. In this regard the effect of plasma on death of the cancer cells are explored experimentally. The plasma in this discharge is created by pulsed dc high voltage power supply with repetition rate of several tens of kilohertz which led to the inductively coupled plasma. The pure helium gas were used for formation of the plasma jet. MTT assay were used for quantification of death cells. The results showed that the cells death rate increase with plasma exposure time. This study confirm that plasma jet have significant effect on treatment of human breast cancer cells.

SESSION UF2: HIGH PRESSURE DISCHARGES II

Friday Morning, 26 October 2012
Room: Classroom 203 at 9:00
Brian Sands, Universal Energy Systems, presiding

Contributed Papers

9:00

UF2 1 Photon Emission Dynamics during Low-Temperature Plasma Formation* ANDREW FIERRO, GEORGE LAITY, ANDREAS NEUBER, LYNN HATFIELD, *Texas Tech University* This paper discusses the experimentally observed dynamics of photon emission in the vacuum ultraviolet (VUV) and ultraviolet (UV) spectral regions during the early formation phase of pulsed atmospheric plasma with nanosecond resolution. A 40 kV high voltage pulse with 100 ns risetime is utilized to breakdown a variable millimeter sized gap in various gases at atmospheric pressure.

Spatially-resolved PMT measurements reveal that early photon emission originates near the anode and that the source of VUV emission travels from anode to cathode at a velocity on the order of 10^7 cm/s, which is consistent with streamer velocities in volume breakdown reported elsewhere. It is also found, for instance, in pure nitrogen that the second positive system is the main contributor to the emitted light spectrum between 200 to 800 nm during the plasma formation phase while atomic nitrogen dominates the wavelength range between 115 to 200 nm. Under the investigated conditions, it is further elucidated that excited atomic nitrogen is formed in a two-step process rather than in a single electron collision with molecular nitrogen. Current observations in H_2 discharges demonstrate strong self-absorption for the Lyman-alpha transition coupled with appreciable Stark line broadening.

*Work supported by the AFOSR with additional student fellowship support provided by the NPSC.

9:15

UF2 2 Micro-Plasma Discharges From Charge Rollers in Print Engines* JUN-CHIEH WANG, *University of Michigan* NAPOLEON LEONI, HENRYK BIRECKI, OMER GILA, *HP Research Labs* MARK J. KUSHNER, *University of Michigan* Conductive charge rollers (CR) are components in print engines of, for example, laser printers for charging of photoconductor (PC) surfaces. The charging results from an atmospheric plasma produced between the biased CR and the PC. During charging, the PC behaves like a perfect insulator with a conductivity $< 10^{-15}/\Omega \cdot$ cm. The charging process is essentially that of a dielectric-barrier-discharge. If operated with a dc or quasi-dc voltage, the discharge is terminated by surface charges on the PC. The charging process is continuous as the CR and PC surfaces move at speeds of tens to hundreds of cm-s^{-1}. The discharge is then reignited as the voltage drop between the CR and incoming uncharged surface of the PC rebounds. In this investigation, multi-dimensional computer modeling of the CR to PC charging process has been conducted. The computer model, *nonPDPSIM*, solves transport equations for charged and neutral species, Poisson's equation, and the electron energy conservation equation for electron temperature. A Monte Carlo simulation is used to track sheath accelerated secondary electrons and the energy of ions incident onto surfaces. Radiation transport is included. We found that the applied voltage waveform and material properties of CR are important to operation. The uniformity of surface charges on the PC is sensitive to the material properties and speed of the moving surface. Parametric results for uniformity of charging of the PC will be discussed.

*Work supported by HP Research Labs.

9:30

UF2 3 Slow Lightning in Water Plasmoids* KARL STEPHAN, SHELBY DUMAS, JONATHAN MCMINN, *Ingram School of Engineering, Texas State University-San Marcos* Water plasmoids are produced when a capacitor is discharged into a cathode at the surface of a weakly conducting water electrolyte. The resulting plasma jet forms a glowing spherical plasmoid which persists in air for up to 0.3 s and resembles ball lightning in some respects. This study shows that during the plasmoid's formation stage, surface discharges with unusual characteristics carry the large instantaneous discharge current. The liquid-surface discharges have some characteristics of both conventional solid-surface discharges (branching, fractal structure) and glow discharges (approximately constant current density from the discharge plasma to the water surface over a wide range of current). Dynamically, the surface discharge resembles a two-dimensional version of a lightning leader, but develops at much lower speeds: a maximum of about 0.3 m/s for the surface discharges in this study, compared to lightning leader speeds of 100 to 100,000 m/s. The low conductivity of the water used (about 20 mS/m) means that the surface discharges are interacting with a resistive barrier, which allows a significant tangential electric field on the surface. High-speed photography of the discharges is supplemented by spectroscopic and other experimental studies.

*The authors acknowledge support provided by a Texas State University 2012 Research Enhancement Grant.

9:45

UF2 4 High-Voltage Discharge in Air and Nitrogen, Guided by Femtosecond Laser* SERGEY LEONOV, *JIHT RAS* JAMES MICHAEL, RICHARD MILES, MICHAIL SHNEIDER, *Princeton University* MICHAIL SHURUPOV, *JIHT RAS* JIHT RAS TEAM, PRINCETON UNIVERSITY TEAM The ability of a low energy (El < 2mJ), femtosecond laser pulse to modify a high energy (Ed > 1J), high voltage discharge is examined in detail. The geometry and breakdown voltage of a long filamentary submicrosecond high-voltage pulse discharge are studied by noting the effect on initial streamer formation, the breakdown location and overall geometry, and through voltage and current waveforms. The laser pulse is focused in the inter-electrode gap, producing a weakly-ionized plasma filament and effectively decreasing the high voltage breakdown and the geometry of both the initial streamer formation and the high voltage filamentary breakdown. The electric pulse is characterized by rapid voltage rise, dU/dt > 2×10E11 V/s. High voltage breakdown results in a current pulse of 30-80ns with voltage amplitude of up to 120 kV. The guiding effect is considered for delay times up to 100mcs. The initial stage of breakdown – development a streamer tree – was observed in detail. Tests were performed in air and nitrogen to better illuminate the physical mechanism of our observed laser-based guiding, particularly at small (less 2 mcs) and large (up to 100 mcs) delays. The largest decrease in the breakdown voltage occurs at early time, and the effect remains significant in pure nitrogen at delay times up to 5 mcs. Both gas kinetic and gas-dynamic analyses are used to determine the effects due to ionization and density drops in both air and nitrogen.

*Work is supported by AFOSR.

10:00

UF2 5 Phase-resolved excitation dynamics of a pulsed 13.56 MHz asymmetric surface barrier discharge in atmospheric-pressure argon JAMES DEDRICK, *The Australian National University* DEBORAH O'CONNELL, TIMO GANS, *University of York* ROD BOSWELL, CHRISTINE CHARLES, *The Australian National University* SPACE PLASMA, POWER AND PROPULSION LABORATORY TEAM, YORK PLASMA INSTITUTE TEAM Atmospheric-pressure discharges with non-thermal ions and electrons are an active topic of international research. This is because the excitation of reactive species, without extensive vacuum systems and significant heat dissipation in the sample, facilitates the surface modification of sensitive materials in a practical and cost-effective way. Asymmetric surface barrier discharges (ASBDs) are a variant of the parallel-plate barrier discharge, whereby the electrodes are offset and the ionisation region is between one electrode and the dielectric, i.e. Propagation occurs over the surface of the insulator with relatively easy access to the sample. Phase-resolved optical emission spectroscopy has been used to study the breakdown behavior of a pulsed 13.56 MHz ASBD in atmospheric-pressure argon. Two directions of observation and the calculation of the electron-impact excitation from the electronic ground state facilitate the study of highly repeatable streamer dynamics and the propagation of distinct ionisation fronts.

10:15

UF2 6 COMSOL Modeling of Transport of Neutral Radicals to Substrate Surfaces Located Downstream from an Atmospheric Pressure Weakly Ionized Plasma Reactor ROKIBUL ISLAM, WILLIAM LEKOBOU, ERIK WEMLINGER, PATRICK PEDROW, *Washington State University* An Atmospheric Pressure Weakly Ionized Plasma (APWIP) Reactor generates a significant number of charged particles and neutral radicals. In our work the carrier gas is argon and the precursor molecule is acetylene. The APWIP is generated by corona discharges associated with an array of high voltage metal needles facing a grounded metal screen. Neutral radical transport downstream from the grounded screen to the substrate via diffusion and convection will be modeled with COMSOL, a finite element software package. Substrates will include objects with various shapes and characteristic dimensions that range from nanometers to centimeters. After the model is validated against canonical problems with known solutions, thin film deposition rates will be compared with experimentally measured results. Substrate geometries will include discs, spheres, fibers and highly porous surfaces such as those found on asphalt road surfaces. A single generic neutral radical will be used to represent the entire family of neutral radicals resulting from acetylene bond scission by free electron impact.

10:30

UF2 7 Precursor ionization ahead of laser-supported detonation wave in air and argon KOHEI SHIMAMURA, KIMIYA KOMURASAKI, *Graduated School of Frontier Sciences, University of Tokyo* HIROYUKI KOIZUMI, *Research Center for Advanced Science and Technology, the University of Tokyo* YOSHIHIRO ARAKAWA, *Graduated School of Engineering, the University of Tokyo* Laser-produced plasma in a gaseous form is considered, which has attracted great interest for use in many devices. After breakdown one of possible mechanisms of occurrence of this process is noted as laser-supported detonation wave. This wave consisting of the shock wave and the beam absorbing plasma travels at several kilometers per second along the laser beam channel in the direction opposite to the beam incidence. A Nd: Glass laser and a TEA CO_2 laser were utilized. According to shadowgraph and spectroscopic studies, the wave has a velocity of 1–10 km/s, an electron temperature of 2–5 eV and an electron density of 10^{24} m^{-3} after breakdown. For simplicity, the discussion is restricted to one-dimensional flows that considers the radiation from plasma and the collisional ionization by laser irradiation. Assuming that UV photons radiating from laser plasma induce photoionization ahead of ionization front, this ionization frequency f_p at the distance l_p (mean free path of photon) from the wave front corresponds to 10^{10} s^{-1}. This is higher than the collisional ionization frequency (10^{5-6} s^{-1}). Analytical velocities ($f_p l_p$) describing the avalanche ionization in the pre-ionization layer agree with the experimentally observed velocities. These results does not depend on background gas and laser-wavelength.

10:45

UF2 8 Numerical studies of filamentary plasma formation in high power millimeter wave field TENSEI TAKEICHI, TOSHIKAZU YAMAGUCHI, MASAFUMI FUKUNARI, HIROYUKI KOIZUMI, KIMIYA KOMURASAKI, YOSHIHIRO ARAKAWA, *The University of Tokyo* Filamentary structure characterizes millimeter-wave discharge in air and the ionization front propagates at supersonic speed in a high power millimeter-wave, generating a shock wave. In this study, the filamentary structure was studied experimentally and analytically using a 170 GHz Gyrotron at the peak intensity range of 50 kW/cm^2 to 200 kW/cm^2. On the propagation process of ionization front, it is important to investigate steady plasma formation process in a filamentary form through millimeter wave. Each filamentary element observed in the ionization front propagates not along or perpendicular to the electric field, but obliquely. To solve this mechanism, 2-dimensional numerical analysis was conducted assuming this phenomenon as a plasma fluid model. In dozens of times the size of plasma element scale, the steady plasma structure formation was simulated, and the calculation was compared with previous experimental results. The calculated formation patterns were in good qualitative agreement with experiments. The calculation model provides a physical interpretation of the pattern formation and dynamics. From the interpretation, it was found that accurate ionization model in low electric field is needed for good agreement with experiments. Moreover, for a quantitative agreement, not only the ionization model but also consideration of 3-dimensional effects are necessary, since 2-dimensional simulation cannot estimate accurate wave reflection and interaction by plasma.

SESSION UF3: PLASMA DIAGNOSTICS TECHNIQUES II

Friday Morning, 26 October 2012
Room: Classroom 202 at 9:00
Ed Barnat, Sandia National Laboratories, presiding

Contributed Papers

9:00

UF3 1 Temperature measurement of substrate with a thin film using low-coherence interference TAKAYOSHI TSUTSUMI, TAKEHIRO HIRAOKA, KEIGO TAKEDA, KENJI ISHIKAWA, HIROKI KONDO, *Nagoya University* TAKAYUKI OHTA, MASAFUMI ITO, *Meijo University* MAKOTO SEKINE, MASARU HORI, *Nagoya University* In plasma etching or plasma CVD, substrate temperature is one of the most important factors which determine the process performances. Non-contact temperature measurement technology is preferred for the fabrication of electric devices because of avoiding contamination and improving reliability. We have developed a highly precise and non-contact temperature monitor using a Fourier domain low-coherence interferometer (FD-LCI) and a super luminescent diode (SLD; center wavelength: 1330 nm, spectral width: 37.6 nm) as a low coherence light source. The temperature is derived from the changes of optical path length in substrate, which occurred by thermal expansion and refractive-index change. We achieved to estimate the Si wafer temperature during a plasma exposure. However, it is necessary to measure a substrate with thin films and/or other material substrate such as sapphire. In this report, we applied the monitor to Si wafer with carbon nanowalls and a sapphire substrate with GaN. While on heating the substrate, the optical path length increased linearly, and it turned out that non-contact measurement of substrate with a thin film could be realized for Si and sapphire substrates.

[1]T. Tsutsumi et al., ISPlasma2011, P1-002A, Nagoya, Japan, (March 2011).

9:15

UF3 2 Significance of self-absorption for emission spectral lines* EVGUENI GUDIMENKO, VLADIMIR MILOSAVLJEVIC, STEPHEN DANIELS, *Dublin City University* Accurate optical measuring techniques of spectral lines are needed for low pressure plasma semiconductor manufacturing diagnostics. One spectral line broadening problem which has been widely overlooked and its importance neglected is self-absorption. Self-absorption is an effect when a photon emitted by an atom may be absorbed by a different atom before it escapes from the source. In this study the method used to quantify the self-absorption involves changing the optical path length of the measured OES plasma spectral emission. This is achieved by taking OES measurements from two different viewports on the reactive ion etch (RIE) plasma chamber, one directly on top of the plasma chamber and the other on the side of the chamber, both differ in optical length. If the increase in signal intensity changes corresponding to optical length, there is no self-absorption. The experiments are performed in an RIE chamber, 13.56 MHz with maximum RF power of 600 W, Ar - O_2 mixture. Almost all the measured spectral lines have been affected by self-absorption e.g. the Argon 750 nm spectral line has its intensity affected by up to 40%. In the case of Actinometry calculation, taking into account Ar and O_2 emission, correction of self-absorption could change the final result up to 20%.

*This material is based upon works supported by Science Foundation Ireland under grant No.08/SRC/I1411.

9:30

UF3 3 Surface vibrational relaxation of N_2 studied by infrared titration with time resolved Quantum Cascade Laser diagnostics D. MARINOV, O. GUAITELLA, A. ROUSSEAU, *LPP, Ecole Polytechnique, UPMC, Universite Paris Sud, CNRS* D. LOPATIK, M. HÜBNER, J. RÖPCKE, *INP Greifswald* YU IONIKH, *Saint-Petersburg State University Institute of Physics* Relaxation of vibrationally excited nitrogen molecules on reactor walls is the most efficient $N_2(v)$ loss mechanism in laboratory plasmas at pressures up to few tens of mbars. In the present study a new method for determination of the de-excitation probability γ_{N2} of vibrationally excited N_2 on different surfaces has been developed. A short dc discharge pulse was applied to a mixture containing 0.05-1% of CO_2, N_2O or CO in N_2 at 1.3 mbar. Due to a very efficient vibrational coupling between $N_2(v)$ and CO_2 (N_2O, CO), the vibrational excitation of these titrating molecules is an image of the vibrational excitation of N_2. In the afterglow, the vibrational relaxation was monitored *in-situ* using quantum cascade laser absorption spectroscopy. The measurements were performed in a single discharge pulse without signal accumulation. Experimental results were interpreted in terms of a numerical model of non-equilibrium vibrational kinetics. The value of γ_{N2} was determined from the best agreement between the measured and calculated relaxation times. Using new technique the relaxation probability of $N_2(v)$ was measured for SiO_2, TiO_2, Al_2O_3, Pyrex and anodized aluminum.

9:45

UF3 4 Fine structure of Balmer-α line of atomic hydrogen measured by saturation spectroscopy SHUSUKE NISHIYAMA, *Hokkaido University, Japan* GOTO MOTOSHI, *National Institute for Fusion Science, Japan* KOICHI SASAKI, *Hokkaido University, Japan* Saturation spectroscopy is a widely used technique to obtain Doppler-free resolution in fundamental spectroscopy. This technique, however, is not used commonly for plasma diagnostics. In this work, we developed a system of saturation spectroscopy at the Balmer-α line of atomic hydrogen with the intention of applying it to diagnostics of the Large Helical Device at the National Institute for Fusion Science. A weak probe beam and a intense pump beam were injected into a linear magnetized plasma source on the chord of the cylindrical axis of the plasma from the counter directions. The frequency of the probe and pump beams was scanned simultaneously over the whole range of the Doppler-broadened Balmer-α line. In the condition of a weak magnetic field (60 Gauss), we obtained a saturation spectrum with many obvious peaks without Zeeman splitting. Most of the other peaks were assigned to fine-structure components of the Balmer-α line and their cross-over signals, which arose at the midpoint frequency of two transition peaks with a common lower or upper level. We also found anomalous cross-over signals at the midpoint of the peaks which had $2s$ and $2p$ as their lower levels. These signals suggest that the populations of $2s$ and $2p$ are exchanged significantly.

10:00

UF3 5 Measurement of activated species generated by 60 Hz excited atmospheric pressure Ar plasma in atmospheric gas KEIGO TAKEDA, JEROME JOLIBOIS, KENJI ISHIKAWA, HIROMASA TANAKA, *Graduate School of Engineering, Nagoya University* HIROYUKI KANO, *NU Eco-Engineering Co., Ltd.* MAKOTO SEKINE, MASARU HORI, *Graduate School of Engineering, Nagoya University* Atmospheric pressure plasmas have a wide field of applications. To improve the performance, it needs to diagnose the behaviors of activated species generated by plasma discharge and to study about the gas-phase reactions in atmospheric pressure. Moreover, plasma treatments are frequently carried out under atmospheric condition without purge gases. In this study, behaviors of activated species generated by the atmospheric pressure plasma under atmospheric condition have been measured by using LIF spectroscopy. Firstly, concentration of the grand state nitrogen monoxide (NO) was measured. The wavelength of laser light for the excitation of NO was 226.3 nm. The fluorescence was observed on A-X(0, 2) band around 247 nm. The AC excited atmospheric pressure plasma with pure Ar gas was generated under atmospheric condition. The flow rate of Ar gas was fixed at 3 slm. The atmospheric condition was the humidity of 40% and ambient temperature of 25 °C. Concentration of NO has been measured as a function of distance from a jet slit of plasma head. The length of plasma jet was around 10 mm. The results show that the concentration of NO has a maximum at 10 mm from plasma head, and then decreases. This means that the influence of ambient gases was largest in the edge region of plasma.

10:15

UF3 6 Plasma Parameters of SRF Cavities for Radio-Frequency Discharge Processing JANARDAN UPADHYAY, SVETOZAR POPOVIC, LEPSHA VUSKOVIC, *Old Dominion University* ANNE-MARIE VALENTE-FELICIANO, LARRY PHILLIPS, *Jefferson Lab* Superconducting radio frequency (SRF) cavities of bulk Niobium are accelerating field-generating components of particle accelerators. Cavities are designed to support TM modes at a resonant frequency, which usually serve as their identifier. RF plasma surface modification dry-etching technology as an alternative to the currently existing wet etching technology requires a different RF coupling regime. The choice of power generator frequency greatly affects the field and plasma parameters distribution over the cavity. These are adjusted by a coaxial centerline antenna to provide for optimum level of plasma sheath uniformity. In the search for best etching conditions, we are opting for radio frequency (13.56 MHz, 100 MHz) and microwave frequency plasma (2.45 GHz) in Ar/Cl_2 gas mixture. We have developed five optical probes for simultaneous spectroscopic measurements of the plasma properties at five points inside the cavity. The electron temperature and density measurement at the same set of points will be also measured with a Langmuir probe. The measurement of plasma parameters at different pressure and power for the chosen frequency set with varying chlorine content will be presented.

10:30
UF3 7 Convection-Diffusion Model for Atmospheric Pressure Plasma Jets: Obtaining Off-Axis Data from On-Axis Measurements ANSGAR SCHMIDT-BLEKER, MARIO DÜNNBIER, JÖRN WINTER, *ZIK plasmatis at the INP Greifswald e.V.* KLAUS-DIETER WELTMANN, *INP Greifswald e.V.* STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* An analytical convection-diffusion model for atmospheric pressure plasma jets is presented. The model can be applied both for ambient air species diffusion and for heat transfer into a jets effluent. Using on-axis data from experiments as input, the model can be used to extrapolate the measured quantities to the complete domain for laminar flows and near-axis region for turbulent flows. The method is applied to experimental data obtained from molecular beam mass spectrometry as well as from a VUV absorption spectrometry method using the plasma jet itself as a VUV emitter. The measurements are conducted on a turbulent atmospheric pressure argon plasma jet with a protective gas nozzle, allowing for the creation of a shielding gas curtain around the plasma jets effluent. The results obtained from the hybrid analytical-experimental method are compared to computational fluid dynamics simulations.

SESSION UF4: PLASMA DEPOSITION AND PHOTOVOLTAIC APPLICATIONS
Friday Morning, 26 October 2012; Room: Salon DE at 9:00; Masaharu Shiratani, Kyushu University, presiding

Invited Papers

9:00
UF4 1 Investigation of high power impulse magnetron sputtering (HIPIMS) discharge using fast ICCD camera
ANTE HECIMOVIC, *Research Department Plasmas with Complex Interactions, Institute for Experimental Physics II, Ruhr-Universität Bochum, Germany*

High power impulse magnetron sputtering (HIPIMS) combines impulse glow discharges at power levels up to the MW range with conventional magnetron cathodes to achieve a highly ionised sputtered flux. The dynamics of the HIPIMS discharge was investigated using fast Intensified Charge Coupled Device (ICCD) camera. In the first experiment the HIPIMS plasma was recorded from the side with goal to analyse the plasma intensity using Abel inversion to obtain the emissivity maps of the plasma species. Resulting emissivity maps provide the information on the spatial distribution of Ar and sputtered material and evolution of the plasma chemistry above the cathode. In the second experiment the plasma emission was recorded with camera facing the target. The images show that the HIPIMS plasma develops drift wave type instabilities characterized by well defined regions of high and low plasma emissivity along the racetrack of the magnetron. The instabilities cause periodic shifts in the floating potential. The structures rotate in ExB direction at velocities of 10 km s^{-1} and frequencies up to 200 kHz. The high emissivity regions comprise Ar and metal ion emission with strong Ar and metal neutral emission depletion. A detailed analysis of the temporal evolution of the saturated instabilities using four consequently triggered fast ICCD cameras is presented. Furthermore working gas pressure and discharge current variation showed that the shape and the speed of the instability strongly depend on the working gas and target material combination. In order to better understand the mechanism of the instability, different optical interference band pass filters (of metal and gas atom, and ion lines) were used to observe the spatial distribution of each species within the instability.

Contributed Papers

9:30
UF4 2 Reactive high power impulse magnetron sputtering J.T. GUDMUNDSSON, *Shanghai Jiao Tong University* F. MAGNUS, *Uppsala University, Sweden* T.K. TRYGGVASON, O.B. SVEINSSON, S. OLAFSSON, *Science Institute, University of Iceland* Here we discuss reactive high power impulse magnetron sputtering sputtering (HiPIMS) [1] of Ti target in an Ar/N_2 and Ar/O_2 atmosphere. The discharge current waveform is highly dependent on both the pulse repetition frequency and discharge voltage. The discharge current increases with decreasing frequency or voltage. This we attribute to an increase in the secondary electron emission yield during the self-sputtering phase of the pulse, as nitride [2] or oxide [3] forms on the target. We also discuss the growth of TiN films on SiO_2 at temperatures of 22–600 °C. The HiPIMS process produces denser films at lower growth temperature and the surface is much smoother and have a significantly lower resistivity than dc magnetron sputtered films on SiO_2 at all growth temperatures due to reduced grain boundary scattering [4].

[1]J. T. Gudmundsson, N. Brenning, D. Lundin, and U. Helmersson, J. Vac. Sci. Technol. A **30**, 030801 (2012).
[2]F. Magnus, O. B. Sveinsson, S. Olafsson, and J. T. Gudmundsson, J. Appl. Phys. **110**, 083306 (2011).
[3]F. Magnus, T. K. Tryggvason, S. Olafsson, and J. T. Gudmundsson, J. Vac. Sci. Technol., submitted 2012.
[4]F. Magnus, A. S. Ingason, S. Olafsson, and J. T. Gudmundsson, IEEE Elec. Dev. Lett., accepted 2012.

9:45
UF4 3 Control Capabilities of Reactive Sputter Deposition Process via ICPs Driven by Low-Inductance Antenna for Large-Area Formation of Thin Film Devices YUICHI SETSUHARA, KOSUKE TAKENAKA, *Joining and Welding Research Institute, Osaka University* AKINORI EBE, *EMD Corporation* Novel plasma-enhanced reactive sputter-deposition system has been developed with a new type of low-inductance antenna (inner-type LIA) consisting of an RF antenna conductor with a length much shorter than the RF wavelength, which is embedded in a hall region dug in the chamber wall and the dielectric window plate for insulation. This new type of the reactive sputter-deposition system has been developed for enhancement of sputter discharge and excellent control of reactivity during film growth. The ICP-enhanced sputter system has been applied to film formations of microcrystalline silicon (intrinsic layer) and transparent amorphous oxide

semiconductor, a-InGaZnO4 (a-IGZO), aiming at low-temperature formation of high-quality functional films for development of next-generation flexible devices. The newly developed process can offer independent control of the flux ratio of the reactive species (ions and radicals) to the deposited species sputtered out of the target. With this new method, micro-crystalline silicon films with crystallinity of 74% and a-IGZO films with mobility as high as 18 $cm^2(Vs)^{-1}$ have been successfully formed without substrate heating. Furthermore, for development of large-area deposition, uniformity control capabilities with a linear rectangular sputter target with 500 mm length have been examined via variation of power deposition profiles with multiple LIAs.

10:00

UF4 4 Source gas depletion in narrow metal tube during internal DLC coating with microwave-excited high-density near plasma* RYOSUKE MATSUI, HIROYUKI KOSAKA, NORITSUGU UMEHARA, *Department of Mechanical Science and Engineering, Graduate School of Engineerig, Nagoya University* In internal DLC (Diamond-Like Carbon) coating to mm-sized narrow metal tubes by using MVP (Microwave-sheath Voltage combination Plasma) method, axially uniform distribution of film thickness can be obtained by repeating the depletion and homogenization of source gas in a coated tube during plasma-on time T_{on} and plasma-off time T_{off} of pulsed plasma generation, respectively. DLC was deposited to the inner surface of a stainless-steel tube 4.4 mm in inner diameter and 50 mm in length with small holes of $\Phi = 0.4$ mm fabricated at every 10 mm, where the flow rates of Ar and methane were controlled to be 14 and 2 sccm, respectively, at a total gas pressure of 80 Pa. A pulsed negative voltage of −200 V was applied to the tube at a pulse frequency of 10 Hz and duty ratio of 3.2%, synchronizing a pulsed injection of 2.45-GHz microwaves at the same pulse frequency ($T_{on} = 3.2$ ms and $T_{off} = 96.8$ ms). The high-speed camera image showed that the emission (696, 706 nm) from Ar atom was approximately constant during plasma-on time. On the other hand, the emission (468–474 nm) from C_2 dimer was decreased until $T_{on} = 1.5$ ms, and then converged in a constant value; this is ascribed to the consumption of CH_4 gas which is considered to be a main source of C_2 dimer formation.

*This work was partly supported by a Grant-in-Aid for Young Scientists (B), No. 23760695, from the Japan Society for the Promotion for Science.

10:15

UF4 5 Fabrication of graphene-based films using remote plasma CVD MINEO HIRAMATSU, RYOSUKE TSUKADA, YOHEI KASHIMA, MASATERU NAITO, *Meijo University* HIROKI KONDO, MASARU HORI, *Nagoya University* Plasma-enhanced CVD (PECVD) employing methane/hydrogen gases has been used to grow diamond, diamond-like carbon, and carbon nanotubes. In the case of microwave PECVD with methane/hydrogen system without catalyst nanoparticles at temperatures of 700–850 °C, where the substrate is exposed to the plasma, vertical nano-graphenes and carbon nanoflakes have been easily grown even on Cu substrate due to the ion bombardment and local electric field forces. In this work, we demonstrate the synthesis of planar few-layer graphene-based film using PECVD with remote plasma configuration. In the case using microwave plasma of cylindrical resonant cavity type, by simply installing grounded grid over the substrate plate for obtaining remote plasma configuration, we have successfully fabricated graphene-based films on Cu substrate, which was confirmed by the Raman spectrum and SEM image of deposit. Similar method will be applied to other plasmas such as low-pressure inductively coupled plasma, in order to verify the effectiveness of remote plasma configuration for the growth of planar graphene using PECVD technique. We will discuss the planar graphene growth mechanism in terms of precursors and their surface reaction.

10:30

UF4 6 A plasma-enhanced close-spacing sublimation (PECSS) device for photovoltaic thin-film modification GARRETT METZ, *Colorado State University - Department of Mechanical Engineering* LEN MAHONEY, *Colorado State University Faculty Affiliate* JOHN WILLIAMS, DREW SWANSON, WALAJABAD SAMPATH, *Colorado State University - Department of Mechanical Engineering* A plasma-enhanced, close-spacing sublimation (PECSS) device has been developed for improving CdS deposition on a transparent conductive oxide (TCO)-coated substrate that is part of the plasma production circuit. This unique device and process method makes possible the elimination of pin holes in the CdS transmission layer. In addition the process has been used to incorporate oxygen-dopants within the CdS layer, reducing absorption, and thereby increasing cell efficiency. We review the spatial uniformity of the ion current flux on the TCO-coated substrate when operating with Ar/O_2 and N_2/O_2 by means of in situ surface probes fashioned by laser-scribing strips in the TCO coating. Bulk plasma features of the PECSS device are also reviewed including electron energy and plasma potential. Process utility, modeling, and scaling of the PECSS device are reviewed for pressures of 40–200 mTorr and surface areas of 60–1700 cm^2.

10:45

UF4 7 Investigations of capacitively coupled radio frequency hydrogen and hydrogen/silane discharges SEBASTIAN MOHR, EDMUND SCHÜNGEL, JULIAN SCHULZE, UWE CZARNETZKI, *Ruhr-University Bochum* One of the most important challenges in optimizing capacitively coupled radio frequency discharges for applications such as the deposition of thin films is gaining the independent control of flux and energy of ions and reactive species at the surfaces. This independent control can be obtained by using electrically asymmetric discharges which use two consecutive harmonics to excite the plasma; the ion energy can be controlled by the phase between the two frequencies while the flux stays constant. We conduct two-dimensional simulations of such discharges using the simulation tool Hybrid Plasma Equipment Model by Mark Kushner [1]. The focus of our investigations lies on hydrogen and hydrogen/silane plasmas at pressures up to several 100 Pascals as they are used in the production of solar cells. This presentation deals with the question, how characteristics of these discharges such as field reversals influence the independent control of ion energy and flux. Funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (0325210B).

[1]M. Kushner, J. Phys. D **42**, 194013 (2009).

M

N

O

T

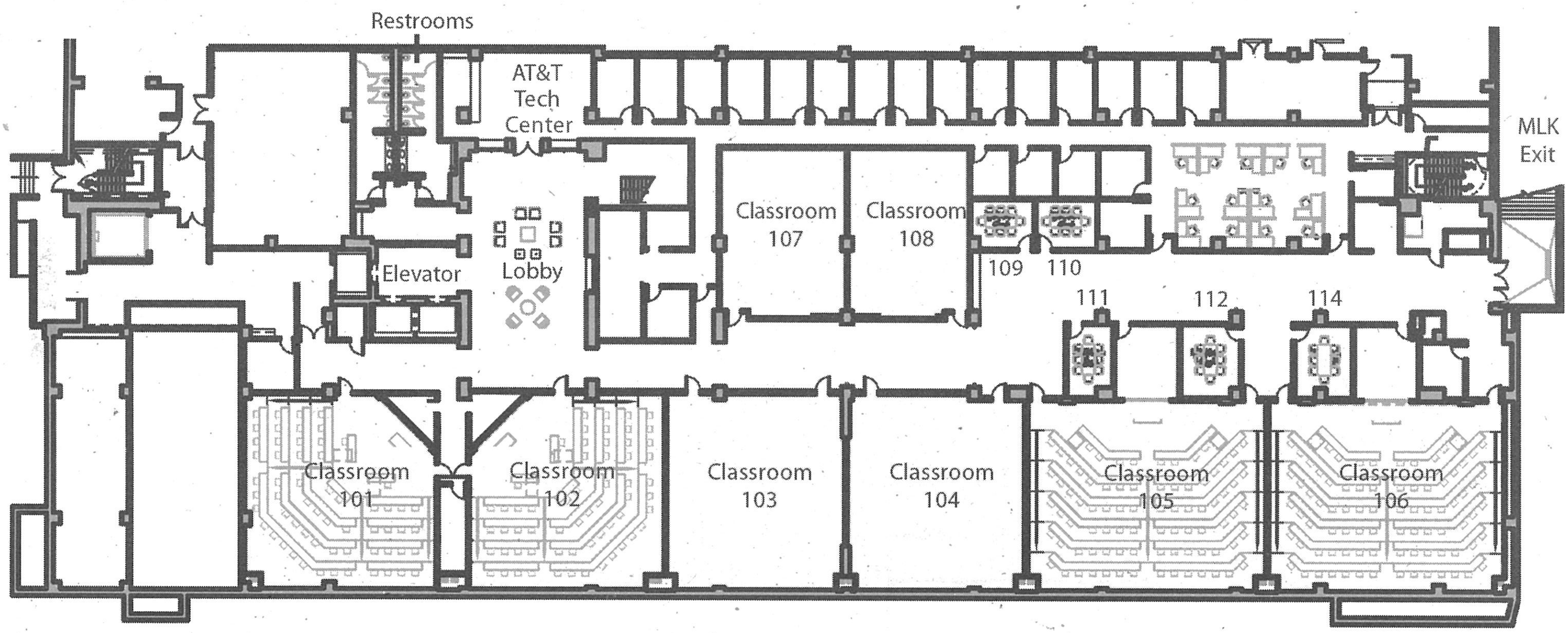
U

V

W

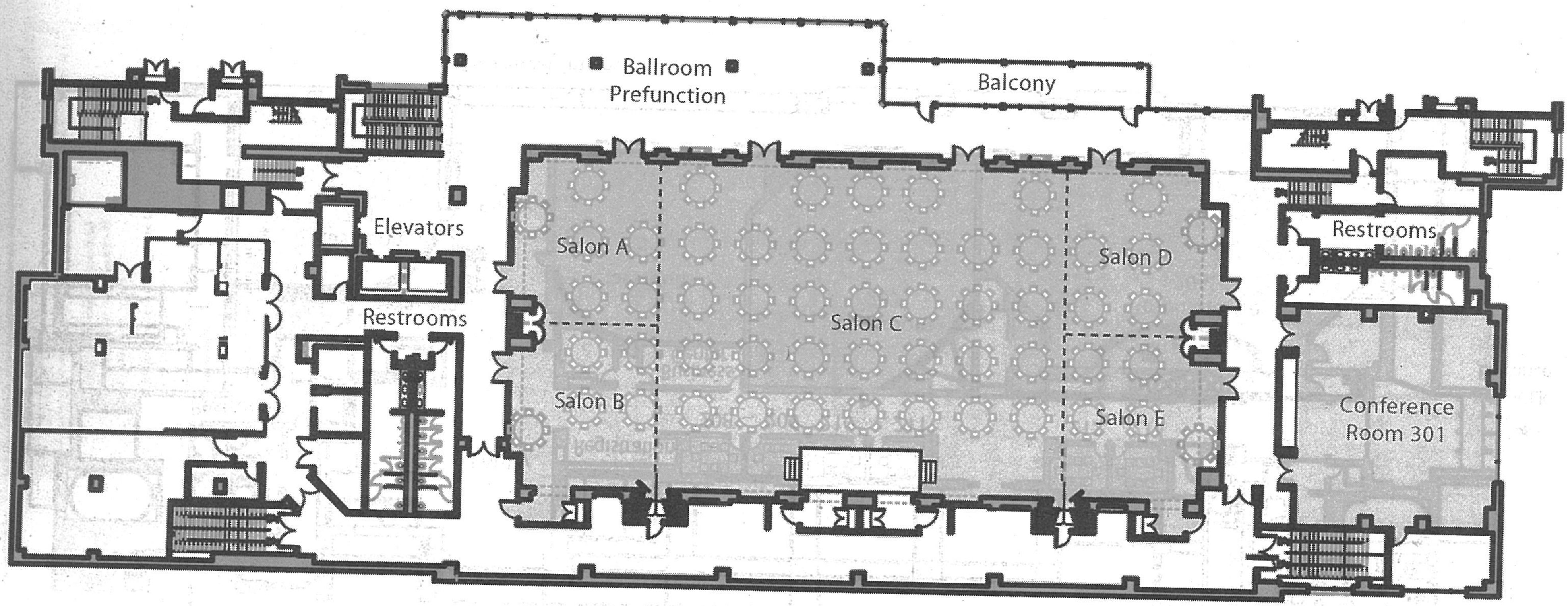
NOTES

AT&T Conference Center
Level One

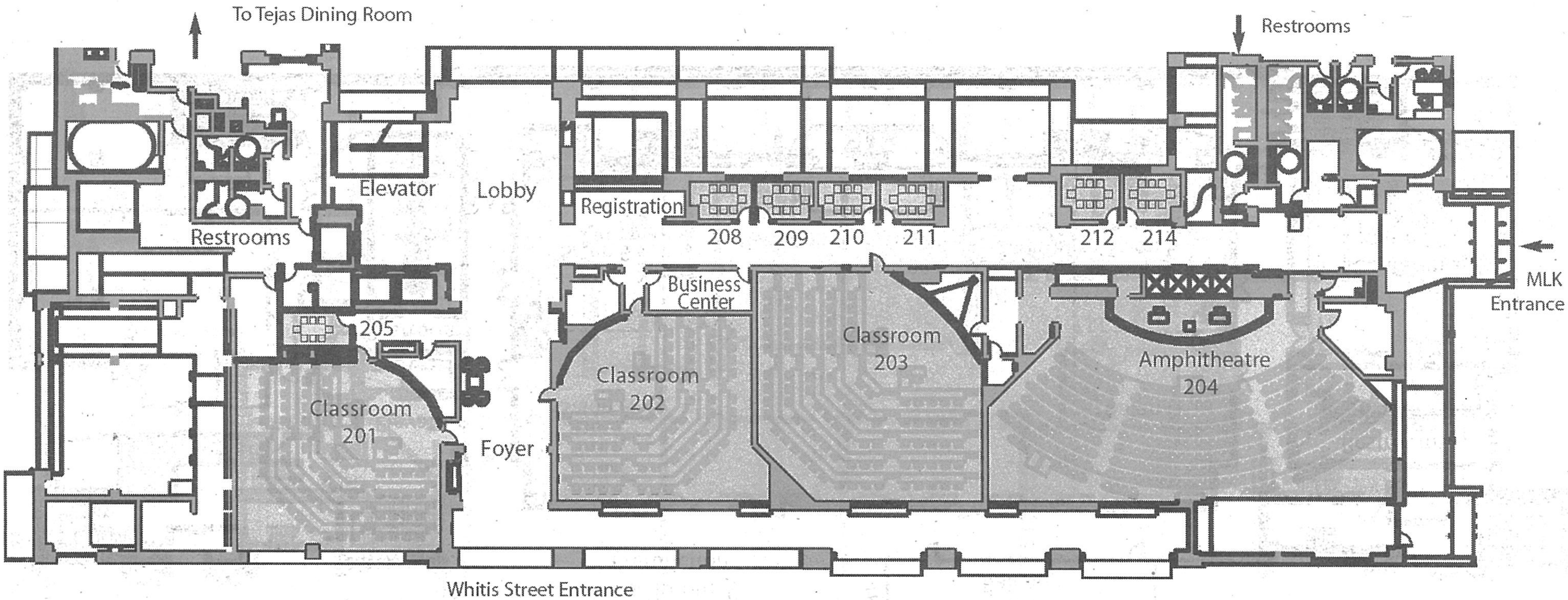


AT&T Conference Center

Level Three



AT&T Conference Center
Level Two



15:30 THURSDAY AFTERNOON
25 OCTOBER 2012

SR1 **Plasma Modeling and Simulations III**
Denis Eremin
Room: Amphitheatre 204

SR2 **Plasma Etching II**
Joelle Margot, Tetsuya Tatsumi
Room: Classroom 203

SR3 **Electron Collisions with Atoms and Molecules**
Leigh Hargreaves, Hidetoshi Kato
Room: Classroom 202

SR4 **Plasmas in Liquids**
Room: Salon DE

09:00 FRIDAY MORNING
26 OCTOBER 2012

UF1 **Biological and Biomedical Applications of Plasmas II**
Room: Classroom 107

UF2 **High Pressure Discharges II**
Room: Classroom 203

UR3 **Plasma Diagnostics Techniques II**
Room: Classroom 202

UR4 **Plasma Deposition and Photovoltaic Applications**
Ante Hecimovic
Room: Salon DE

Epitome of the 65th Annual Gaseous Electronics Conference

08:00 MONDAY MORNING
22 OCTOBER 2012

AM1 — **Workshop on Plasma Biomedicine**
Room: Amphitheatre 204

08:30 MONDAY MORNING
22 OCTOBER 2012

AM2 — **Workshop on Plasma Cross Field Diffusion**
Room: Classroom 203

13:30 MONDAY AFTERNOON
22 OCTOBER 2012

AM3 — **Workshop on Verification and Validation of Low-Temperature Plasma Simulations**
Room: Classroom 202

18:00 MONDAY EVENING
22 OCTOBER 2012

BM1 — **Opening Reception**
Room: Interior Courtyard

08:00 TUESDAY MORNING
23 OCTOBER 2012

CT1 — **Plasma Sheaths I**
Natalia Sternberg
Room: Amphitheatre 204

CT2 — **Plasma Surface Interactions**
Room: Classroom 203

CT4 — **Microdischarges I**
Toshiaki Makabe
Room: Salon DE

10:00 TUESDAY MORNING
23 OCTOBER 2012

DT1 — **Diagnostics I**
Room: Amphitheatre 204

DT2 — **Low Pressure Plasma Sources**
Room: Classroom 203

DT3 — **Green Plasma Technologies**
Haruaki Akashi
Room: Classroom 202

DT4 — **Capacitively Coupled Plasmas**
Room: Salon DE

13:30 TUESDAY AFTERNOON
23 OCTOBER 2012

ET1 — **Nanotechnologies I**
Tatsuru Shirafuji
Room: Amphitheatre 204

ET2 — **Atmospheric Pressure Nanosecond Pulsed Discharges**
Andrey Starikovskiy
Room: Classroom 203

ET3 — **Inductively Coupled Plasmas**
Valery Godyak
Room: Classroom 202

ET4 — **Ion Distribution Functions**
Merritt Funk
Room: Salon DE

15:30 TUESDAY AFTERNOON
23 OCTOBER 2012

FT1 — **Biological and Biomedical Applications of Plasmas I**
Room: Amphitheatre 204

FT2 — **Plasma Modeling and Simulations I**
Peter Ventzek
Room: Classroom 203

FT3 — **Electron-Impact Ionization**
Lorenzo Ugo Ancarani, Allan Stauffer
Room: Classroom 202

FT4 — **Advanced Laser Beam Diagnostics**
Jose Maria Palomares Linares, Walter Lempert
Room: Salon DE

18:00 TUESDAY EVENING
23 OCTOBER 2012

GT1 — **A Scientific Tribute to Professor Lev D. Tsendin**
Room: Classroom 202

19:00 TUESDAY EVENING
23 OCTOBER 2012

GT2 — **Workshop on Plasma Data Exchange Project**
Room: Classroom 203

08:00 WEDNESDAY MORNING
24 OCTOBER 2012

HW1 — **Plasma Sheaths II**
Karl-Ulrich Riemann
Room: Amphitheatre 204

HW2 — **Plasma Etching I**
Lawrence Overzet
Room: Classroom 203

HW3 — **Heavy Particle Collisions**
Daniel Fischer
Room: Classroom 202

10:00 WEDNESDAY MORNING
24 OCTOBER 2012

JW1 — **GEC Foundation Talk**
Klaus Bartschat
Room: Amphitheatre 204

11:00 WEDNESDAY MORNING
24 OCTOBER 2012

KW1 — **Business Meeting**
Room: Amphitheatre 204

13:30 WEDNESDAY AFTERNOON
24 OCTOBER 2012

LW1 — **Nanotechnologies II**
Makoto Kambara
Room: Amphitheatre 204

LW2 — **Basic Plasma Physics Phenomena in Low-Temperature Plasmas**
Room: Classroom 203

LW3 — **Plasma Propulsion I**
Room: Amphitheatre 202

15:30 WEDNESDAY AFTERNOON
24 OCTOBER 2012

MW1 — **High Pressure Discharges I**
Ute Ebert
Room: Amphitheatre 204

MW2 — **Negative Ion and Dust Particle Containing Plasmas**
Ursel Fantz
Room: Classroom 203

MW3 — **Collisions with Biomolecules**
Thomas Orlando, Marcio Varella
Room: Classroom 202

19:00 WEDNESDAY EVENING
24 OCTOBER 2012

NW1 — **Poster Session I (7:00-9:30PM)**
Room: Salon CDE

08:00 THURSDAY MORNING
25 OCTOBER 2012

PR1 — **Poster Session II (8:00-10:00AM)**
Room: Salon CDE

10:00 THURSDAY MORNING
25 OCTOBER 2012

PR3 — **Positrons and Collision Processes in Plasmas**
Ron White, David Cassidy
Room: Classroom 202

10:30 THURSDAY MORNING
25 OCTOBER 2012

QR1 — **Plasma Modeling and Simulations II**
Jan van Dijk
Room: Amphitheatre 204

QR2 — **Non-equilibrium Kinetics**
Room: Classroom 203

QR3 — **Microdischarges II**
Pascal Chabert
Room: TBD

13:30 THURSDAY AFTERNOON
25 OCTOBER 2012

RR2 — **Thermal Plasmas: Arcs, Jets, Switches, Others**
Room: Classroom 203

RR3 — **Plasma Propulsion II**
Yevgeny Raitses
Room: Classroom 202

RR4 — **Microdischarges III**
Leanne Pitchford
Room: Salon DE

0003-0503(201210)57:8;1-U