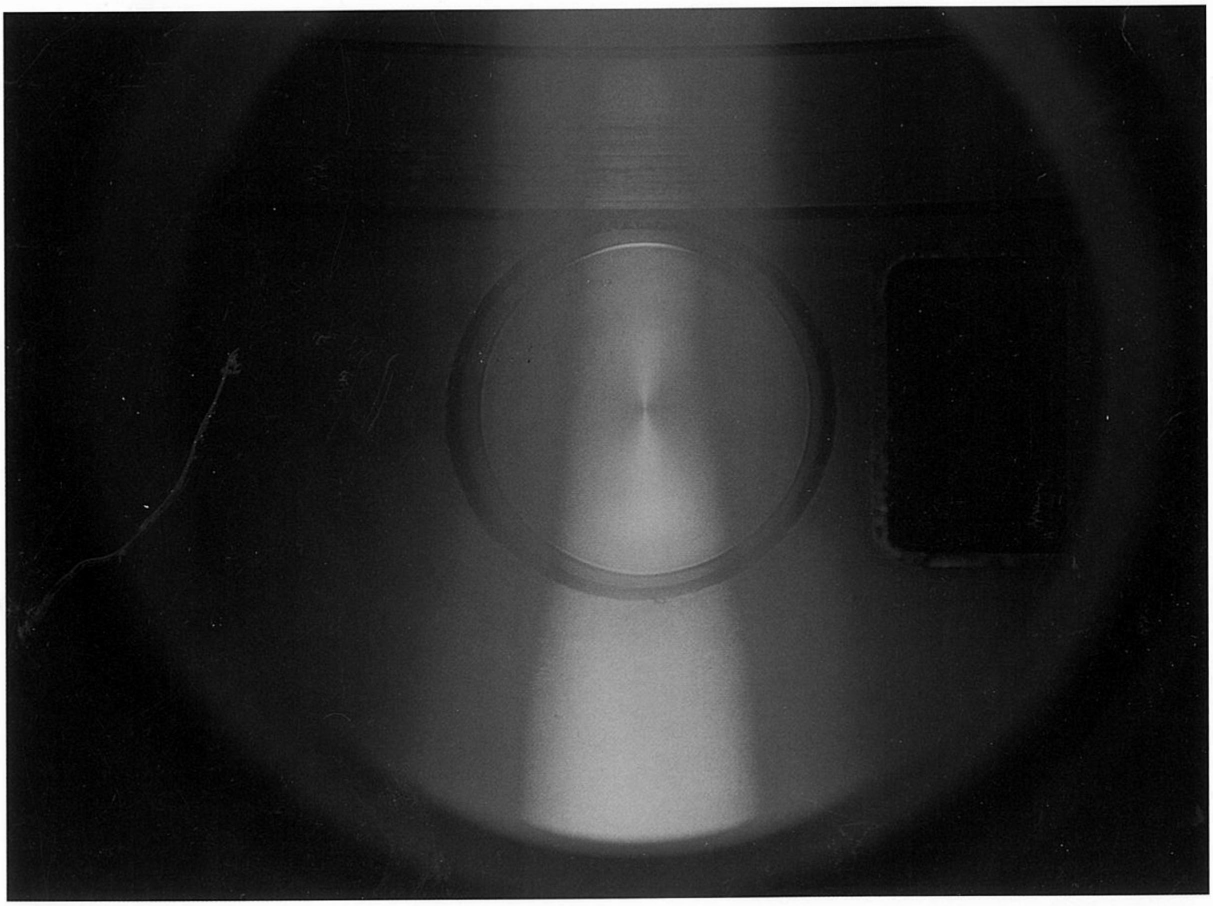
BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

69th Annual Gaseous Electronics Conference

October 10–14, 2016

Bochum, Germany



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

69th Annual Gaseous Electronics Conference

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69th Annual Gaseous Electronics Conference

October 10–14, 2016
Bochum, Germany

GENERAL INFORMATION

Welcome to the Ruhr-University Bochum, honored to organize the 69th GEC! The university is located in the midst of the dynamic and hospitable metropolitan area of the Ruhr, in the heart of Europe. The Ruhr-University Bochum (RUB) with its 20 faculties and many disciplinary institutional units is home to 5,600 employees and over 41,000 students from 130 countries. All the great scientific disciplines are united on one compact campus. RUB is proud of its particular strength in plasma science. On campus, the Research Department Plasmas with Complex Interactions coordinates activities in the plasma field and takes an active role in organizing the 69th GEC.

The GEC is a special meeting of the Division of Atomic, Molecular and Optical Physics (DAMOP) of the American Physical Society (APS). It promotes the exchange of scientific information and viewpoints concerning basic phenomena in the field of gaseous electronics. GEC has been held annually since 1948. Since then it is only the fourth time that the meeting takes place outside the US, after Montreal/Canada 1993, Bunratty/Ireland 2004, and Paris/France 2010.

For 68 years, the GEC has been an invaluable resource to the plasma and collision community, and continues to have a leadership presence in traditional areas such as plasma phenomena, low pressure processes, plasma chemistry, surface interactions, atomic and molecular interactions, simulation, and diagnostics. In recent years, the GEC has also taken a leadership role in the emerging areas of plasma science such as biological and environmental applications and atmospheric plasma systems.

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

The conference will bring together over 450 scientists and engineers from around the world who will attend 42 invited talks, 222 oral contributed talks, and 262 poster presentations. The GEC program includes four workshops on Monday, an opening reception on Monday evening, and a Thursday evening awards banquet. In addition, an industry exhibition will take place along the conference.

The GEC prides itself in student attendance. The conference will present the "Student Award for Excellence" to the best student oral presentation, selected from a group of 4 finalists.

SPECIAL SESSIONS AND EVENTS

The GEC Executive Committee is pleased to announce that the Will Allis Prize for the Study of Ionized Gases will be presented by Klaus Bartschat from Drake University, USA. His talk, "Electron Collisions: Experiment, Theory, and Applications," is at 10:30 am on Wednesday, October 12, in the Auditorium Maximum (Audimax) lecture hall. Four workshops will be held on Monday:

SESSION AM2:
Plasma Kinetics
Monday, October 10 • 11:00 am

SESSION AM4:
Pulsed High Power Plasmas for Synthesis of Nanostructured Thin Films
Monday, October 10 • 11:00 am

SESSION BM3:
Future Challenges in Plasma Physics
Monday, October 10 • 1:00 pm

SESSION BM1:
Electrification of the chemical industry
Monday, October 10 • 10:00 am

LXCAT DISCUSSION ON WEDNESDAY

LXCat (www.lxcat.net) is an open-access, web-based platform for storing, exchanging, and manipulating data needed for the electron and ion components in cold, non-equilibrium plasmas. Over 40 people from institutions around the world have so far contributed to this project, and the data are widely used by members of the GEC community. An informal meeting to discuss questions, suggestions and future plans for the LXCat project will be held on Wednesday, October 12th, 2016. If you are a current/future user or contributor, or if you are simply interested in knowing more about the project, please plan to attend. For further information or to suggest agenda items before the meeting, please contact Sergey Pancheshnyi at sergey.pancheshnyi@ch.abb.com. The workshop will be in room 2B.

SESSION NUMBERING SCHEME

Each session code consists of a letter and a number. The first letter indicates the number of that session in the program, e.g. A for 1, B for 2 etc. The second letter indicates the day of the week: M for Monday, T for Tuesday, W for Wednesday, R for Thursday, and F for Friday. The last number (1-4) is the index used to distinguish the concurrent sessions (see table below for room assignments). The plenary session on Wednesday will take place in the Auditorium Maximum (Audimax), and the poster sessions will be held in the Audimax (Foyer).

SESSION INDEX	ROOM
1	1
2	2 A
3	2 B
4	3

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 in Audimax will contain two posters on each side, each poster with a size of 84,1 x 118,9 cm (size DinA0). The posters may remain on display throughout the day and have to be removed at the close of each day (Tuesday and Wednesday evenings by 8:00 pm).

GEC STUDENT AWARD FOR EXCELLENCE

The GEC Executive Committee will award a US$1,000 prize for best oral presentation by a student. Their advisor must have nominated a student before being selected by GEC Executive Committee members to present and compete for the Excellence Award. Student award finalists will present their work between Tuesday, October 11 and Thursday, October 13. Students competing for the award, in order of their listing in the GEC 2016 program are:

Bret Scheiner, University of Iowa
Tuesday, October 11 • 11:00–11:15 am
Room 2a, ET2.1.

Adam Obrusnik, Masaryk University
Wednesday, October 12 • 09:15–09:30 am
Room 2b, JW3.3.

Naoyuki Kurake, Nagoya University
Thursday, October 13 • 02:30–02:45 pm
Room 2b, SR3.2.

Sandra Schröter, University of York
Thursday, October 13 • 05:00–05:15 pm
Room 2b, TR3.5.

At the 68th GEC in Honolulu, Hawaii, the GEC Student Award for Excellence was shared between: Bastien Bruneau, Ecole Polytechnique, Palaiseau, France, and Jannis Teunissen, Center for Mathematics & Computer Science(CWI), Amsterdam, Netherlands.

REGISTRATION

The registration desk will be located at the Audimax. Registration hours are:
Monday, October 10 • 8:00 am to 6:00 pm
Tuesday, October 11 • 8:00 am to 5:30 pm

The on-site registration fees are:

Regular Attendee	EUR 600
Retired/Unemployed	EUR 300
Student	EUR 300
Guest Banquet Ticket	EUR 70

OPENING RECEPTION AND BANQUET

An opening reception will be held from 6:00 pm to 8:00 pm on Monday, October 10, in the Audimax Foyer. On Thursday evening, October 13, the banquet reception will be held at 6:00 pm, Henrichs, Gebläsehalle, Werksstraße 31-33, Hattingen (http://www.henrichs-restaurant.de/), followed by the banquet from 7:00 pm to 11:00 pm featuring live entertainment. Prior to the banquet there are five guided tours to the old blast furnace. Please register for those at the information desk in the Audimax! Bus transportation between RUB and Henrichs will be provided for all participants at 5:30 pm (for the guided tours) and 6:30 pm (for the banquet only) and after the banquet back to Bochum Main Station (city center). The cost of the banquet is included in the attendee's registration fee. Banquet guest tickets may be purchased for EUR 70 online. The GEC Awards for Best Student Oral and Poster Presentations will be presented during the banquet.

LAB TOURS

There will be four lab tours on Tuesday, October 11, 7:30 pm, and four lab tours on Wednesday, October 12, 7:00 pm. Each tour takes 60 minutes and covers two different laboratories. The groups hosting the lab tours are:

- Experimental Physics II: Chair for "Physics of Reactive Plasmas" and Research Group "Coupled Plasma-Solid State Systems".
- Experimental Physics V: Chair for "Plasma and Atomic Physics"
- Chair for "Electrical Engineering and Plasma Technology"
- Research Group "Biomedical Applications of Plasmas"

Register for the lab tours at the info board, located in the Audimax Foyer next to GEC registration.

WI-FI

Wi-Fi access is complimentary in the conference center. You will receive a personalized login account on your confirmation of registration. The account is valid October 10–14. If your home organization provides "eduroam" access, you can use the same configuration like at home. Just open your laptop and start surfing.Attendees who do not have "eduram" access use the personalized login account on your confirmation of registration and follow these instructions:

- WPA-Type: WPA/WPA2 Enterprise
- Key-Type: TKIP or AES
- EAP-Method: TTLS
- Authentication-Type: PAP
- Anonymous identity: anonymous@ruhr-uni-bochum.de

You can find more information about our wireless access on the web:
www.rz.ruhr-uni-bochum.de/dienste/netze/wlan

AUDIOVISUAL EQUIPMENT

The technical sessions will be equipped with an LCD projector and amplified sound. Dell Laptops will be provided for the oral sessions. All laptops will be equipped with Windows 7 Prof. 64bit, Acrobat Reader, PowerPoint 2013, Windows Media player 12 and VLC 2.1.1. Presentations need to be uploaded before the session to the laptop provided. Experience shows that saving your presentation as a PDF file (with embedded fonts) avoids potential conversion problems between PC and Macintosh computers. If presenters wish/need to use their own computer, any setup delay will be counted against their allotted presentation time.

DINING OPTIONS

The dining options on campus include

- Main dining hall "Mensa" (11:00 am – 2:30 pm)
- Smaller dining hall "Bistro" (11:00 am – 4:00 pm)
- Cafeteria in direct vicinity of the conference rooms (8:00 am – 6:00 pm)
- Restaurant "Q-West" (9:00 am – 10:00 pm)
- Cafeteria "Edwards" on campus / at main library (9:00 am – 8:00 pm)

Other places to eat can be found in the shopping center (Uni-Center) near the university subway station.

PUBLIC TRANSPORT

Each participant will receive a ticket for free use of public transport (subway, bus, tram) from their hotel to RUB and back for the full length of the meeting (October 10–14). It takes about 9 minutes from the central railway station "Hauptbahnhof" to the university by subway line U35 (direction: Bochum Hustadt). Please get off at "Ruhr-Universität". Information on the public transport system in Bochum can be found under http://www.bogestra.de/tickets-%26tarife/streckenplaene.html

CALL FOR NOMINATIONS FOR GEC GENERAL AND EXECUTIVE COMMITTEES

The GEC Executive Committee welcomes nominations, including self-nominations, for both the General Committee and the Executive Committee. Becoming a General Committee and/or Executive Committee member provides a unique opportunity to participate in GEC governance and future conference direction. General Committee and Executive Committee members decide on selection of special event topics, invited speakers, abstract-sorting categories, arranging the technical program, selection of meeting sites, and budgetary decisions. Please review the GEC constitution for details

At the GEC Business Meeting new members of the GEC General Committee will be selected (the nominees must be attending the Business Meeting). General Committee meets once a year during the GEC annual conference. The Executive Committee meets twice a year: during the GEC annual conference and during the summer at the Sorters Meeting.

The 2016 Business Meeting will take place on Wednesday, October 12, at 12:00 after the group photo in front of the Audimax. Written proposals to host future GEC meetings are encouraged and should be discussed with the Chair of the Executive Committee. The General Committee reviews all proposals and makes the final site selection. The selected host is then elected to a 3-year term on the Executive Committee as Secretary-Elect, then Secretary, and finally as Past Secretary.

CALL FOR INVITED SPEAKER RECOMMENDATIONS FOR THE 70TH GEC

At the 68th GEC in Hawaii, the GEC Executive Committee solicited recommendations for invited speakers from GEC members. About half of invited speakers at the 69th GEC were recommendations accepted by the Executive Committee.

This year the GEC Executive Committee will again solicit recommendations for invited speakers from GEC members. As specified by the GEC constitution, the Executive Committee will make the final selection of the invited speakers for the 70th GEC.

Invitations to submit recommendations will be sent by email, along with a link to the submission web site. Please only use the web portal for submitting recommendations.

PUBLICATION OF INVITED SPEAKER ARTICLES IN PLASMA SOURCES SCIENCE & TECHNOLOGY

All GEC invited speakers are invited to submit their conference article to the IOP journal Plasma Sources Science and Technology. Articles are required to contain at least 30% of new and unpublished research and need to be within the scope of the Journal. The articles will be reviewed to the usual Journal standards and published as regular papers. Once all the articles are published they will be gathered in a web page dedicated to the 69th GEC and free to download for a period of time. This year, the Guest Editors are Prof. Lorenzo Ugo Ancarani (Université de Lorraine), Dr. Costel Biloiu (Applied Materials, Inc.), Prof. John Foster (University of Michigan), and Prof. Uwe Czarnetzki (Ruhr-University Bochum). Please contact the Guest Editors to submit your GEC invited talk article to the Journal.

GEC 2016 EXECUTIVE COMMITTEE

Chair: Mirko Vukovic, Member of Technical Staff, TEL Technology Center, America

Chair Elect: Tom Kirchner, Associate Professor, York University

Secretary: Uwe Czarnetzki, Professor, Ruhr-University Bochum

Secretary Elect: Earl Scime, Jefimenko Professor, West Virginia University

Past Secretary: Klaus Bartschat, Ellis & Nelle Levitt Professor, Drake University

Treasurer: Michael Schulz, Curators' Professor, Missouri University of Science & Technology

DAMOP/Appointed: Thomas Miller, Senior Research Physicist, Boston College Inst. for Sci. Res.

General Members:

Allison Harris, Assistant Professor, Illinois State University

Kallol Bera, Sr. Member of Technical Staff, Applied Materials, Inc.

Matthew Hopkins, Member of Technical Staff, Sandia National Laboratories

Mounir Laroussi, Professor, Old Dominion University

Koichi Sasaki, Professor, Hokkaido University

Appointed Members:

Anne Bourdon, Research Director, LPP, CNRS, Ecole Polytechnique

John Foster, Professor, University of Michigan

David Staack, Associate Professor, Texas A&M University

MEMBERS OF GEC 2016 LOCAL ORGANIZING COMMITTEE

Uwe Czarnetzki, Professor Experimental Physics V, Ruhr-University Bochum

Verena M. Scharf, Science Manager RD Plasma, Ruhr-University Bochum

Susanne Hentrich, Secretary Experimental Physics V, Ruhr-University Bochum

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GEC 2016 SPONSORS

Sponsors and Exhibitors allow the GEC Executive Committee to provide many benefits to attendees including student travel assistance and an excellence award for junior attendees. The 69th 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.

GOLD SPONSORS:

Deutsche Forschungsgemeinschaft (DFG)
National Science Foundation (US)
Robeko, Magpuls, Plasus
Tokyo Electron, Inc.
Sandia National Laboratories and the Department of Energy (US)

SILVER SPONSORS:

LAM Research Corporation
Applied Materials, Inc.

BRONZE SPONSORS:

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Due to generous support of sponsors, we have been able to accommodate most student requests for travel assistance!

GEC 2016 EXHIBITORS

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Impedans
Inficon
Institute of Physics (IOP)
Neoplas, neoplas control, neoplas tools
Pfeiffer
Plasmetrex
PLASUS / Robeko / Magpuls
Quantemol
Radiant Dyes Laser Acc. GmbH
Roper Scientific
Sirah Lasertechnik GmbH
Springer EPJD
Toptica
Zurich Instruments

Epitome of the 2016 Annual Fall Meeting of the Gaseous Electronics Conference

10:00 MONDAY MORNING
10 OCTOBER 2016

BM1 **Electrification of the Chemical Industry**
David Graves, Richard van de Sanden, Ming Chen, Gerard van Rooij, Vasco Guerra, Rune Ingels, Sander van Bavel, Laurent Fulcheri, Ali Mesbah, Jurgen Lang
Room: Room 1

11:00 MONDAY MORNING
10 OCTOBER 2016

AM2 **Plasma Kinetics**
Ron White, Gerjan Hagelaar, Helge Redvald Skullerud, Sasa Dujko, Jens Oberrath, Lee Chen
Room: Room 2a

AM3 **Pulsed High Power Plasmas for Synthesis of Nanostructured Thin Films**
Arutiun Ehiasarian, Diederik Depla, Grzegorz Greczynski, Kostas Sarakinos, Tiberiu Minea, Christian Maszl, Nikolay Britun
Room: Room 2b

13:00 MONDAY AFTERNOON
10 OCTOBER 2016

BM3 **Future Challenges in Plasma Physics**
Gerrit Kroesen, Pascal Chabert, Igor Kaganovich, Luis Alves, Bill Graham, Peter Bruggeman, Michael Bonitz, Thomas Klinger, Masaru Hori, Yi-Kang Pu, Mark Kushner
Room: Room 3

18:00 MONDAY AFTERNOON
10 OCTOBER 2016

CM1 **Opening Reception**
Room: Foyer

08:30 TUESDAY MORNING
11 OCTOBER 2016

DT1 **Electrical Diagnostics I**
Alan Howling
Room: 1

DT2 **Computational Plasma Modeling**
Room: 2a

DT3 **Chemical Kinetics/Combustion & Environmental**
Nikolay Popov
Room: 2b

11:00 TUESDAY MORNING
11 OCTOBER 2016

ET1 **Negative Ion Complex, and Dust Particle Containing Plasmas**
Room: 1

ET2 **Sheaths/Plasma Physics**
Greg Severn
Room: 2a

ET3 **Plasma Liquid Interactions**
Keisuke Takashima, Toshiro Kaneko
Room: 2b

14:00 TUESDAY AFTERNOON
11 OCTOBER 2016

FT1 **Optical Emission Spectroscopy**
Room: 1

FT2 **Inductively Coupled Plasmas I**
Room: 2a

FT3 **Microplasmas**
Ayyaswamy Venkattraman
Room: 2b

FT4 **Plasma Deposition I**
Room: 3

16:00 TUESDAY AFTERNOON
11 OCTOBER 2016

GT1 **Plasma Propulsion and Aerospace Applications I**
Christine Charles
Room: 1

GT2 **Capacitively Coupled Plasmas I**
Room: 2a

GT3 **Discharges in Liquids I**
Tsuyohito Ito
Room: 2b

GT4 **Magnetrons I**
Room: 3

17:30 TUESDAY EVENING
11 OCTOBER 2016

HT6 **Poster Session I**
Room: Foyer

08:30 WEDNESDAY MORNING
12 OCTOBER 2016

JW1 **Antimatter Collisions and Ionization Processes**
Gaetana Laricchia, Lorenzo Ugo Ancarani
Room: 1

JW2 **Capacitively Coupled Plasmas II**
Aranka Derzsi
Room: 2a

JW3 **Atmospheric Plasma Jets and Sources I**
Sander Nijdam
Room: 2b

JW4 **Plasma Propulsion and Aerospace Applications II**
Room: 3

10:30 WEDNESDAY MORNING
12 OCTOBER 2016

KW1 **The Will Allis Prize for the Study of Ionized Gases**
Klaus Bartschat
Room: 1

17:30 WEDNESDAY EVENING
12 OCTOBER 2016

MW6 **Poster session II**
Room: Foyer

15:00 WEDNESDAY AFTERNOON
12 OCTOBER 2016

NW1 **Laser-Based Diagnostics I**
Edward Barnat
Room: 1

NW2 **Plasma Etching**
Hisataka Hayashi
Room: 2a

NW3 **Surface and Dielectric Barrier Discharges**
Room: 2b

NW4 **Basic Plasma Physics I**
Room: 3

08:30 THURSDAY MORNING
13 OCTOBER 2016

QR1 **Heavy Particle Collisions**
Xavier Urbain, Luis Mendez
Room: 1

QR2 **Plasma Surface Interaction**
Masaaki Matsukuma, Shahid Rauf
Room: 2a

QR3 **Streamer and Breakdown Processes**
Zdeněk Bonaventura
Room: 2b

QR4 **Basic Plasma Physics II**
Peter Hartmann
Room: 3

**11:00 THURSDAY MORNING
13 OCTOBER 2016**

RR1 **Electrical Diagnostics II**
Keiji Nakamura
Room: 1

RR2 **Plasma Deposition II**
Room: 2a

RR3 **Discharges in Liquids II**
Room: 2b

RR4 **Electro-Magnetic Interactions with Plasmas I**
Jeffrey Hopwood
Room: 3

**14:00 THURSDAY AFTERNOON
13 OCTOBER 2016**

SR1 **Electron-Molecule Collision Data for Plasma Modelling**
Michael Brunger, Jonathan Tennyson
Room: 1

SR2 **Inductively Coupled Plasmas II**
Room: 2a

SR3 **Biological Applications of Plasma I**
Masafumi Jinno
Room: 2b

SR4 **Electro-Magnetic Interactions with Plasmas II**
Room: 3

**16:00 THURSDAY AFTERNOON
13 OCTOBER 2016**

TR1 **Laser-Based Diagnostics II**
Thomas Trottenberg
Room: 1

TR2 **Magnetrons II**
Room: 2a

TR3 **High Pressure Plasma Chemistry**
Room: 2b

TR4 **Atmospheric Plasma Jets and Sources II**
Room: 3

**18:00 THURSDAY EVENING
13 OCTOBER 2016**

TR6 **Reception and Banquet**
Room: Henrichs Gebläsehalle, Hattingen

**08:30 FRIDAY MORNING
14 OCTOBER 2016**

UF1 **Electron-Impact Collisions**
Alexander Dorn, C. P. Ballance
Room: 1

UF2 **Chemical Modeling**
Jan van Dijk, Mario Capitelli
Room: 2a

UF3 **Thermal Plasmas**
Room: 2b

**11:00 FRIDAY MORNING
14 OCTOBER 2016**

VF1 **Electron Collisions with Small Molecules**
Leigh Hargreaves, Åsa Larson
Room: 1

VF2 **Capacitively Coupled Plasmas III**
Room: 2a

VF3 **Biological Applications of Plasma II**
Room: 2b

SESSION AM2: PLASMA KINETICS
Monday Morning, 10 October 2016; Room: Room 2a at 11:00; Satoshi Hamaguchi Zoran Petrovic, Peter Ventezek Osaka University, Japan; Institute of Physics, Belgrade; Toyko Electron, presiding

Invited Papers

11:00
AM2 1 Challenge for more precise e- and ion-transport in gases and liquids*
RON WHITE, *James Cook University*

The full potential of technologies driven by non-equilibrium electron and ion processes in gases, liquids and soft-matter can only be realised once the basic physics has been mastered. The central component in this pursuit is an ever increasing need for the precise determination of electron and ion transport in such media. Over the last few decades, the group at James Cook University and collaborators have developed a suite of multi-term Boltzmann equation solutions to treat temporal and spatial non-locality for electrons and ions in electric and magnetic fields in gaseous systems. In this presentation, we will highlight recent developments including (i) a space-time multi-term solution of Boltzmann's equation; (ii) a unified treatment of electron and ion solutions of Boltzmann's equation which avoids mass ratio expansions; (iii) the treatment dense gases and liquids, including coherent scattering, screened potentials and (self) trapped bubble state effects, the latter of which can give rise to fractional transport behaviour, and (iv) the application to consider the self-consistency of cross-sections for electrons in biomolecules.

*Contributors: G. Boyle, P. Stokes, M. Casey, N. Garland, D. Cocks, D. Konovalov, S. Dujko, R. E. Robson, K. F. Ness, M. Brunger, S. Buckman, J. de Urquijo and Z. Lj. Petrovic. Support: Australian Research Council.

11:30
AM2 2 Effect of Coulomb collisions on low temperature plasma characteristics
GERJAN HAGELAAR, *LAPLACE, CNRS and University of Toulouse*

This presentation discusses the effects of electron-electron and electron-ion Coulomb collisions on the electron distribution function and transport coefficients obtained from the Boltzmann equation for simple gas discharge conditions. Such Boltzmann results are commonly used as inputs for fluids models or to interpret experimental data, but usually without taking into account Coulomb collisions. Proper inclusion of Coulomb collisions in the Boltzmann equation involves complex nonlinear collision terms acting on both the isotropic and anisotropic parts of the distribution function. In this presentation, different Coulomb collision effects are illustrated on the basis of local Boltzmann calculation results for argon gas. It is shown that the anisotropic part of the electron-electron collision term, generally neglected in the low-temperature plasma literature, can in certain cases have a large effect on the electron mobility and is essential when describing the transition towards the Coulomb collision dominated regime characterized by Spitzer transport coefficients. Finally, a brief overview is presented of the discharge conditions for which different Coulomb collision effects occur in different gases.

Contributed Papers

12:00
AM2 3 Lunch Break

Invited Papers

13:30
AM2 4 Developments in the kinetic theories of ion and electron swarms in the 1960's and 70's
HELGE REDVALD SKULLERUD, *Retired*

The two decades from 1960 to 1980 saw a quite fantastic development in diverse areas in physics, and so also in the quantitative treatment and deeper understanding of the behaviour of isolated electrons and ions in gases – that is "charged particle swarm physics". This evolution was strongly correlated with the contemporary advances in computer technology, and of new and accurate experimental methods for finding the charged particle transport parameters, as drift velocities, diffusion coefficients and reaction rates', as well as with development in neighbouring fields as plasma physics and the physics of electronic and molecular collisions. In 1960, low energy electron behaviour could already be calculated with reasonable accuracy in the so-called two-term approximation, while ion behaviour could only be treated at very weak elecric fields. By 1980, though, reasonably complete theories had been developed for perhaps most cases in interest - which is reflected in a number of reviews, books and journal articles published in the early 80's. We will give a guided tour through the developments in this period and the basic theories behind; The Boltzmann equation in difference-differential form (for electrons), or in integral equation form (preferred by mathematicians), and the Maxwell transfer equations ("moment theories"). We will also indicate how the interaction between different studies of the same basic processes have led to the elimination of shortcomings, and a better understanding, choosing a few test cases for illustration.

14:30

AM2 5 Kinetic and fluid descriptions of charged particle swarms in gases and nonpolar fluids: Theory and applications

SASA DUJKO, *Institute of Physics, University of Belgrade, Serbia*

In this work we review the progress achieved over the last few decades in the fundamental kinetic theory of charged particle swarms with the focus on numerical techniques for the solution of Boltzmann's equation for electrons, as well as on the development of fluid models. We present a time-dependent multi term solution of Boltzmann's equation valid for electrons and positrons in varying configurations of electric and magnetic fields. The capacity of a theory and associated computer code will be illustrated by considering the heating mechanisms for electrons in radio-frequency electric and magnetic fields in a collision-dominated regime under conditions when electron transport is greatly affected by non-conservative collisions. The kinetic theory for solving the Boltzmann equation will be followed by a fluid equation description of charged particle swarms in both the hydrodynamic and non-hydrodynamic regimes, highlighting (i) the utility of momentum transfer theory for evaluating collisional terms in the balance equations and (ii) closure assumptions and approximations. The applications of this theory are split into three sections. First, we will present our 1.5D model of Resistive Plate Chambers (RPCs) which are used for timing and triggering purposes in many high energy physics experiments. The model is employed to study the avalanche to streamer transition in RPCs under the influence of space charge effects and photoionization. Second, we will discuss our high-order fluid model for streamer discharges. Particular emphases will be placed on the correct implementation of transport data in streamer models as well as on the evaluation of the mean-energy-dependent collision rates for electrons required as an input in the high-order fluid model. In the last segment of this work, we will present our model to study the avalanche to streamer transition in non-polar fluids. Using a Monte Carlo simulation technique we have calculated transport coefficients for electrons in liquid argon and liquid xenon. We employ the two model processes in which only momentum and only energy are exchanged to account for structure dependent coherent elastic scattering at low energies. The specific treatment of inelastic collisions in our model will be also discussed using physical arguments.

Contributed Papers

15:00

AM2 6 Coffee Break

Invited Papers

15:30

AM2 7 Kinetic modeling of active plasma resonance spectroscopy*

JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lueneburg, Germany*

The term "active plasma resonance spectroscopy" (APRS) refers to a plasma diagnostic method which employs the natural ability of plasmas to resonate close to the plasma frequency. Essential for this method is an appropriate model to determine the relation between the resonance parameters and demanded plasma parameters. Measurements with these probes in plasmas of a few Pa typically show a broadening of the spectrum that cannot be predicted by a fluid model. Thus, a kinetic model is necessary. A general kinetic model of APRS probes, which can be described in electorstatic approximation, valid for all pressures has been presented [1]. This model is used to analyze the dynamic behavior of such probes by means of functional analytic methods. One of the main results is, that the system response function $Y(\omega)$ is given in terms of the matrix elements of the resolvent of the dynamic operator evaluated for values on the imaginary axis. The spectrum of this operator is continuous which implies a new phenomenon related to anomalous or non-collisional dissipation. Based on the scalar product, which is motivated by the kinetic free energy, the non-collisional damping can be interpreted: In a periodic state, the probe constantly emits plasma waves which propagate to "infinity". The free energy simply leaves the "observation range" of the probe which is recorded as damping. The kinetic damping, which depends on the mean kinetic energy of the electrons, is responsible for the broadening of a resonance peak in the measured spectrum of APRS probes. The ultimate goal is to determine explicit formulas for the relation between the broadening of the resonance peak and the "equivalent electron temperature", especially in the case of the spherical Impedance Probe and the Multipole Resonance Probe.

*Gratitude is expressed to the internal funding of Leuphana University, the BMBF via PluTO+, the DFG via Collaborative Research Center TR 87, and the Ruhr University Research School.

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

16:00
AM2 8 Paradigm shifts in plasma processing and application of fundamental kinetics to problems targeting 5 nm technology device technology
LEE CHEN, *Tokyo Electronic America, Austin*

It is often said that semiconductor technology is approaching the end of scaling. While fundamental device limits do approach, plasma etching has been doing the heavy lifting to supplement the basic limits in lithography. RF plasmas, pulsing in many forms, diffusion plasmas are but a few of the important developments over the last 20 years that have succeeded in the seemingly impossible tasks. The commonality of these plasmas is being self-consistent: their near-Boltzmann EEDf maintains ionization with its tail while providing charge-balance with its T_e. To control the plasma chemistry is to control its EEDf; the entanglement of ionization with charge-balance in self-consistent plasmas places a constraint on the decoupling of plasma chemistry from ionization. Example like DC/RF parallel-plate hybridizes stochastic heating with DC-cathode injected e^- -beam. While such arrangement offers some level of decoupling, it raised more questions than what it helped answered along the lines of beam-plasma instabilities, bounce-resonance ionization, etc. Pure e^- -beam plasmas could be a drastic departure from the self-consistent plasmas. Examples like the NRL e^- -beam system and the more recent TEL NEP (Nonambipolar e^- Plasma) show strong decoupling of T_e from ionization but it is almost certain, many more questions lurk: the functions connecting collisional relaxation with instabilities, the channels causing the dissociation of large fluorocarbons (controlling the ion-to- radical ratio), the production of the damaging deep UV in e^- -beam plasmas, etc., and the list goes on. IADf is one factor on feature-profile and IEDf determines the surgical surface-excitation governing the selectivity, and both functions have T_i as the origin; what controls the e^- -beam plasmas' T_i? RF-bias has served well in applications requiring energetic excitation but, are there ways to improve the IEDf tightness? What are the adverse side-effects of "improved IEDf"? Decades ago an infant RF-plasma was thrown into the dry-etch arena and it hit the ground running with much of the understandings as after the facts. While the etching industry enjoys the heavy lifting by the successful self-consistent plasmas, perhaps time can be used on front-loaded soul searching of the "maybe needed" plasmas, for the future etching needs.

Contributed Papers

16:30
AM2 9 Panel Discussion

SESSION AM3: PULSED HIGH POWER PLASMAS FOR SYNTHESIS OF NANOSTRUCTURED THIN FILMS
Monday Morning, 10 October 2016; Room: Room 2b at 11:00; Peter Awakowicz, Ruhr University, presiding

Invited Papers

11:00
AM3 1 High Power Impulse Magnetron Sputtering - the Age of Adolescence
ARUTIUN EHIASARIAN, *Sheffield Hallam University*

11:30
AM3 2 Lessons from modelling DC reactive magnetron sputtering for HIPIMS users
DIEDERIK DEPLA, *Ghent University*

Contributed Papers

12:00
AM3 3 Lunch Break

Invited Papers

13:30
AM3 4 Synchronized metal-ion irradiation as a way to control growth of transition-metal nitride alloy films during hybrid HIPIMS/DCMS co-sputtering*
GRZEGORZ GRECZYNSKI, *Linköping University*

High-power pulsed magnetron sputtering (HIPIMS) is particularly attractive for growth of transition metal (TM) nitride alloys for two reasons: (i) the high ionization degree of the sputtered metal flux, and (ii) the time separation of metal-

and gas-ion fluxes incident at the substrate. The former implies that ion fluxes originating from elemental targets operated in HIPIMS are distinctly different from those that are obtained during dc magnetron sputtering (DCMS), which helps to separate the effects of HIPIMS and DCMS metal-ion fluxes on film properties. The latter feature allows one to minimize compressive stress due to gas-ion irradiation, by synchronizing the pulsed substrate bias with the metal-rich-plasma portion of the HIPIMS pulse. Here, we use pseudobinary TM nitride model systems TiAlN, TiSiN, TiTaN, and TiAlTaN to carry out experiments in a hybrid configuration with one target powered by HIPIMS, the other operated in DCMS mode. This allows us to probe the roles of intense and metal-ion fluxes ($n = 1, 2$) from HIPIMS-powered targets on film growth kinetics, microstructure, and physical properties over a wide range of M_1M_2N alloy compositions. TiAlN and TiSiN mechanical properties are shown to be determined by the average metal-ion momentum transfer per deposited atom. Irradiation with lighter metal-ions ($M_1 = Al^+$ or Si^+ during M_1-HIPIMS/Ti-DCMS) yields fully-dense single-phase cubic $Ti_{1-x}(M_1)_xN$ films. In contrast, with higher-mass film constituent ions such as Ti^+, easily exceeds the threshold for precipitation of second phase w-AlN or Si_3N_4. Based on the above results, a new PVD approach is proposed which relies on the hybrid concept to grow dense, hard, and stress-free thin films with no external heating. The primary targets, Ti and/or Al, operate in DCMS mode providing a continuous flux of sputter-ejected metal atoms to sustain a high deposition rate, while a high-mass target metal, Ta, is driven by HIPIMS to serve as a pulsed source of energetic heavy-metal ions to densify the dilute TiTaN and/or TiAlTaN alloys. No external heating is used and the substrate temperature does not exceed 120 °C. This development allows for widening the application range of hard TM nitride coatings to new classes of technologically-relevant temperature-sensitive substrates, such as components made by plastics, glasses, aluminum alloys, and tempered steels.

*Author wants to acknowledge the financial support from VINN Excellence Center Functional Nanoscale Materials (FunMat) Grant 2005 02666.

14:00
AM3 5 Control of nanoscale atomic arrangement in multicomponent thin films by temporally modulated vapour fluxes
KOSTAS SARAKINOS, *Linköping University*

Synthesis of multicomponent thin films using vapor fluxes with a modulated deposition pattern is a potential route for accessing a wide gamut of atomic arrangements and morphologies for property tuning. In the current study, we present a research concept that allows for understanding the combined effect of flux modulation, kinetics and thermodynamics on the growth of multinary thin films. This concept entails the combined use of thin film synthesis by means of multiatomic vapor fluxes modulated with sub-monolayer resolution [1], deterministic growth simulations and nanoscale microstructure probes. Using this research concept we study structure formation within the archetype immiscible Ag-Cu binary system showing that atomic arrangement and morphology at different length scales is governed by diffusion of near-surface Ag atoms to encapsulate 3D Cu islands growing on 2D Ag layers [2]. Moreover, we explore the relevance of the mechanism outlined above for morphology evolution and structure formation within the miscible Ag-Au binary system. The knowledge generated and the methodology presented herein provides the scientific foundation for tailoring atomic arrangement and physical properties in a wide range of miscible and immiscible multinary systems.

[1]*A METHOD OF CONTROLLING IN-PLANE COMPOSITIONAL MODULATION*, Patent Pending Application, PCT/EP2014/052831.

[2]V. Elofsson, G. A. Almyras, B. Lü, R. D. Boyd, and K. Sarakinos, Atomic arrangement in immiscible Ag-Cu alloys synthesized far-from-equilibrium, Acta Mater. **110**, 114 (2016).

Contributed Papers

14:30
AM3 6 Coffee Break

Invited Papers

14:45
AM3 7 What can we learn about HiPIMS process from the multidimensional plasma modeling?*
TIBERIU MINEA, *LPGP, University Paris-Sud, CNRS, University Paris-Saclay, Orsay, France*

The modeling of PVD process and especially magnetron plasma is widely reported. The novel way to excite the plasma applying to the cathode very high power pulses brings the temporal dimension to the system together with new phenomena. From the kinetic model of the dense plasma region, so called Ionization Region – IR, one can quantify the global behavior of the plasma parameters during the pulse. The most significant are the plasma composition, especially in the case of reactive gases, the fraction of back-attracted sputtered ions, the rarefaction due to wind effect, but also the discharge heating mechanisms and contribution to the discharge current. From the 2D particle modeling of the plasma new insights are revealed concerning the shape of the dense plasma region, the time evolution of the sheath, the electron energy distribution function, but also the characteristics of the diffusion plasma facing the substrate. Adding the third dimension to the model, the results reveal the complex transport of electrons especially in the azimuthal direction (instabilities and drifts), the formation of spokes and flares, and the strong relation between the secondary emission of electrons from the target and the plasma structuring.

*Warm thanks to Peter Awakowicz and Ante Hecimovic for inviting me to this GEC edition.

15:15
AM3 8 Localized traveling ionization zones and their importance for the high power impulse magnetron sputtering process*
CHRISTIAN MASZL, *Institute of Experimental Physics II, Ruhr-University Bochum*

High power impulse magnetron sputtering (HiPIMS) is a technique to deposit thin films with superior quality. A high ionization degree up to 90% and the natural occurence of high energetic metal ions are the reason why HiPIMS exceeds direct current magnetron sputtering in terms of coating quality. On the other hand HiPIMS suffers from a reduced efficiency, especially if metal films are produced. Therefore, a lot of research is done by experimentalists and theoreticians to clarify the transport mechanisms from target to substrate and to identify the energy source of the energetic metal ions. Magnetron plasmas are prone to a wide range of wave phenomena and instabilities. Especially, during HiPIMS at elevated power/current densities, symmetry breaks and self-organization in the plasma torus are observed. In this scenario localized travelling ionization zones with certain quasi-mode numbers are present which are commonly referred to as spokes. Because of their high rotation speed compared to typical process times of minutes their importance for thin film deposition was underestimated at first. Recent investigations show that spokes have a strong impact on particle transport, are probably the source of the high energetic metal ions and are therefore the essence of HiPIMS plasmas. In this contribution we will describe the current understanding of spokes, discuss implications for thin film synthesis and highlight open questions.

*This project is supported by the DFG (German Science Foundation) within the framework of the Coordinated Research Center SFB-TR 87 and the Research Department "Plasmas with Complex Interactions" at Ruhr-University Bochum.

15:45
AM3 9 Visualizing the ground state particle dynamics in HiPIMS discharges
NIKOLAY BRITUN, *University of Mons*

Contributed Papers

16:15
AM3 10 Closing Remarks

SESSION BM1: ELECTRIFICATION OF THE CHEMICAL INDUSTRY
Monday Morning, 10 October 2016; Room: Room 1 at 10:00;

Invited Papers

10:00
BM1 1 Introduction
DAVID GRAVES UC BERKELEY, RICHARD VAN DE SANDEN DIFFER, *TU/e*

10:15
BM1 2 The benchmark: Electrochemistry and fuel production
MING CHEN DTU

10:55
BM1 3 Plasma as power transfer medium
GERARD VAN ROOIJ, *CO_2 plasma activation DIFFER*

11:35
BM1 4 Nonequilibrium kinetics in N_2 and CO_2
VASCO GUERRA IST, *Portugal*

Contributed Papers

12:15
BM1 5 Lunch break

Invited Papers

13:30
BM1 6 Fusion farming, fossil free fertilizer on the farm by Nitrogen fixation
RUNE INGELS, *N_2 Applied AS*

14:10
BM1 7 Shell activities on renewable energy and chemical conversion
SANDER VAN BAVEL, *Shell, The Netherlands*

14:50
BM1 8 Direct decarbonization of methane by thermal plasma for the co synthesis of carbon black and hydrogen
LAURENT FULCHERI, *Paris tech*

Contributed Papers

15:30
BM1 9 Coffee Break

Invited Papers

16:00
BM1 10 Advanced control of cold atmospheric plasmas
ALI MESBAH, *UC Berkeley*

16:40
BM1 11 Plasmabased Synthesis of Nitrogenoxid - Enabler for CO_2-free Fertilizer Production
JÜRGEN LANG EVONIK

SESSION BM3: FUTURE CHALLENGES IN PLASMA PHYSICS
Monday Afternoon, 10 October 2016; Room: Room 2b at 13:00; Bill Graham, Gerrit Kroesen Peter Burggeman, presiding

Contributed Papers

13:00
BM3 1 Welcome UWE CZARNETZKI, *Ruhr-University Bochum*

Invited Papers

13:10
BM3 2 Plasma regimes: An exploration of physics challenges
GERRIT KROESEN, *TU Eindhoven*

13:30
BM3 3 What could be the role of numerical simulations in our field?
PASCAL CHABERT, *Ecole Polytechnique*

13:50
BM3 4 Overview of Report on Frontiers of Plasma Science Sponsored by the U.S. Department of Energy, Office of Fusion Energy Sciences
IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory*

14:10
BM3 5 Low-temperature plasmas: old drives, new directions
LUIS ALVES, *Instituto Superior Técnico*

Contributed Papers

14:30
BM3 6 Coffee Break

Invited Papers

15:00
BM3 7 Is there any new plasma physics to be found in low temperature plasmas?
BILL GRAHAM, *Queen's University*

15:20
BM3 8 Key scientific questions on the path to saving the world with plasmas: A personal perspective
PETER BRUGGEMAN, *University of Minnesota*

15:40
BM3 9 When a solid meets a plasma - challenges for theory
MICHAEL BONITZ, *CAU Kiel*

16:00
BM3 10 From low to high - plasma physics at the edge of fusion plasmas
THOMAS KLINGER, *Max-Planck-Institute for Plasma Physics*

Contributed Papers

16:20
BM3 11 Break

Invited Papers

16:35
BM3 12 Challenge towards controlling atomic level interactions of plasma with surfaces
MASARU HORI, *Nagoya University*

16:55
BM3 13 Role of education in advancing plasma science
YI-KANG PU, *Tsinghua University*

17:15
BM3 14 The path forward: Summary and Discussion
MARK KUSHNER, *University of Michigan*

SESSION CM1: OPENING RECEPTION
Monday Evening, 10 October 2016; Room: Foyer at 18:00;

SESSION DT1: ELECTRICAL DIAGNOSTICS I
Tuesday Morning, 11 October 2016; Room: 1 at 8:30; Yevgeny Raitses, Princeton Plasma Physics Laboratory, presiding

Invited Papers

8:30
DT1 1 RF inductive probe to measure plasma complex conductivity
ALAN HOWLING, *EPFL, Swiss Plasma Center, CH-1015 Lausanne, Switzerland*

A method for measuring plasma complex electrical conductivity is described by which plasma parameters such as the electron density and the electron-neutral collision frequency can be estimated. The method relies on the measurement of the impedance of an inductive element coupled to the plasma by mutual induction. The mutual inductance due to the plasma coupling is interpreted by applying the complex image method to the plasma medium [1]; it is determined by the plasma skin depth and the distance to the plasma. For high frequency measurements, capacitive coupling must also be accounted for as a first order correction for standing wave (transmission line) effects. It is shown that a hybrid resonant network configuration can be designed to maximize the inductive coupling and minimize the capacitive coupling.

[1]Ph. Guittienne, R. Jacquier, A. A. Howling, and I. Furno, Plasma Sources Sci. Technol. **24**, 065015 (2015).

Contributed Papers

9:00
DT1 2 Active Plasma Resonance Spectroscopy: Evaluation of a fluiddynamic-model of the planar multipole resonance probe using functional analytic methods MICHAEL FRIEDRICHS, *Institute of Product and Process Innovation, Leuphana University Lüneburg* RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum,* JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lüneburg* Measuring plasma parameters, e.g. electron density and electron temperature, is an important procedure to verify the stability and behavior of a plasma process. For this purpose the multipole resonance probe (MRP) represents a satisfying solution to measure the electron density. However the influence of the probe on the plasma through its physical presence makes it unattractive for some processes in industrial application. A solution to combine the benefits of the spherical MRP with the ability to integrate the probe into the plasma reactor is introduced by the planar model of the MRP. By coupling the model of the cold plasma with the maxwell equations for electrostatics an analytical model for the admittance of the plasma is derivated [1,2], adjusted to cylindrical geometry and solved analytically for the planar MRP using functional analytic methods.

[1]M. Lapke *et al.*, Plasma Sources Sci. Technol. **22**, 025005 (2013).
[2]J. Oberrath and R. P. Brinkmann, Plasma Sources Sci. Technol. **23**, 065025 (2014).

9:15
DT1 3 Collisionless Spectral Kinetic Simulation of Ideal Multipole Resonance Probe JUNBO GONG, SEBASTIAN WILCZEK, DANIEL SZEREMLEY, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum* JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lüneburg* DENIS EREMIN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum* WLADISLAW DOBRYGIN, *Functional Materials and Coating Technologies, Robert Bosch GmbH* CHRISTIAN SCHILLING, *Institute of Microwave System, Ruhr University Bochum* MICHAEL FRIEDRICHS, *Institute of Product and Process Innovation, Leuphana University Lüneburg* RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum* *Active Plasma Resonance Spectroscopy* denotes a class of industry-compatible plasma diagnostic methods which utilize the natural ability of plasmas to resonate on or near the electron plasma frequency ω_{pe}. One particular realization of *APRS* with a high degree of geometric and electric symmetry is the *Multipole Resonance Probe (MRP)*. The Ideal *MRP(IMRP)* is an even more symmetric idealization which is suited for theoretical investigations. In this work, a spectral kinetic scheme is presented to investigate the behavior of the *IMRP* in the low pressure regime. However, due to the velocity difference, electrons are treated as particles whereas ions are only considered as stationary background. In the scheme, the particle pusher integrates the equations of motion for the studied particles, the Poisson solver determines the electric field at each particle position. The proposed method overcomes the limitation of the cold plasma model and covers kinetic effects like collisionless damping.

9:30
DT1 4 Electron density measurements in very electronegative plasmas using different diagnostic techniques: theory and experiments DMYTRO RAFALSKYI, *Laboratoire de Physique des Plasmas, Ecole Polytechnique, Palaiseau FRANCE* TREVOR LAFLEUR, *CNES, Ecole Polytechnique* ANE AANESLAND, *CNRS, Ecole Polytechnique* Very electronegative plasmas (known as "ion-ion" plasmas) are used in different applications including material processing, space propulsion and thermonuclear fusion. Diagnostics of ion-ion plasmas can be performed using different probe techniques, including Langmuir and hairpin probes, RF, microwave and optical diagnostics. However, in certain applications (for example, in the electronegative thruster PEGASES [1]), the electron density is too low ($<10^{12}$m^{-3}) to be reliably measured by these standard techniques. This is further complicated by the presence of strong, non-homogeneous, magnetic fields in the plasma ($\sim$200 G) and the relatively small plasma size (few cm). In this work we compare results achieved with a Langmuir probe, and with an independent measurement of the electron density using a matched dipole probe [2]. Measurements are performed in an SF6 plasma with an electronegativity in the range between a few hundred to a few thousand. We show here that though the model itself can correctly describe the plasma-probe interactions, there is a critical value of plasma electronegativity above which the electron density measured with a Langmuir probe can give only an upper limit estimation.

[1]Plasma Sources Sci. Technol. **23**, 044003 (2014).
[2]Phys. Plasmas **22**, 073504 (2015).

9:45

DT1 5 Measurement Of Plasma Parameters In Micro-Discharge By Wall Probe* ALMAZ SAIFUTDINOV, ANATOLY KUDRYAVTSEV, SERGEY SYSOEV, *Saint-Petersburg State University* The increasing scientific and practical interest for glow discharge at high pressure is largely determined by the fact that their use does not require expensive and huge vacuum equipment. The analysis shows that, in contrast to the well-studied positive column (PC), the basic parameters of the plasma negative glow (NG) and Faraday dark space (FDS) of micro-discharges are studied insufficiently. The difficulties of the experimental diagnostics are associated with the fact that for the fixed values of pL with the increasing gas pressure the length of the micro-discharge decreases. And a small size is extremely difficult to diagnose spatial parameters distribution of micro discharges. Since at a small size introducing traditional Langmuir probe into the plasma capacity is not possible technically, it was proposed to use an additional measuring electrode (wall probe) disposed between the cathode and the anode for measurement of the fast EEDF. With its use we have registered EEDF fast electrons produced in the reaction of Penning ionization out of earlier reach range of high-pressure gas (from 20 to 200 Torr). In this paper by using wall probe we measured the basic parameters of NG plasma in micro-discharge in helium in a wide range of pressures. It is shown that the electrons temperature in the NG plasma is low and amounts to few fraction of 1 eV, which differs from the electron temperature in PC plasma. This allows the use of NG plasma for analysis by gas plasma electron spectroscopy.

*Authors thanks RNF (Grant 14-19-00311) for the support.

10:00

DT1 6 A Study of Impedance Relationships in Dual Frequency PECVD Process Plasma DOUGLAS KEIL, EDWARD AUGUSTYNIAK, YUKINORI SAKIYAMA, *Lam Research Corporation* PECVD/ALD TEAM Commercial plasma process reactors are commonly operated with a very limited suite of on-board plasma diagnostics. However, as process demands advance so has the need for detailed plasma monitoring and diagnosis. The VI probe is one of the few instruments commonly available for this task. We present a study of voltage, current, impedance and phase trends acquired by off-the-shelf VI probes in Dual Frequency (DF) 400 kHz/13.56MHz capacitively-coupled plasma (CCP) as typically used for Plasma Enhanced Chemical Vapor Deposition (PECVD). These plasmas typically operate at pressures from 1 to 5 Torr and at RF power levels of $\sim$3 W/cm^2. Interpretation of DF VI probe impedance trends is challenging. Non-linear interactions are known to exist in plasma impedance scaling with low and high frequency RF power. Simple capacitive sheath models typically do not simultaneously reproduce the impedance observed at each drive frequency. This work will compare VI probe observed DF CCP impedance tends with plasma fluid simulation. Also explored is the agreement seen with sheath models presently available in the literature. Prospects for the creation of useful equivalent circuit models is also discussed.

10:15

DT1 7 Combined complementary plasma diagnostics to characterize a 2f plasma with additional DC current with conditioning effects at the chamber wall MICHAEL KLICK, RALF ROTHE, *Plasmetrex GmbH* KYE HYUN BAEK, EUNWOO LEE, *Semiconductor R&D Center, Samsung Electronics Co.* Multiple frequencies and DC current used in a low-pressure plasma rf discharge result in an increased complexity. This needs plasma diagnostics applied, in particular in a plasma process chamber. That is done under manufacturing conditions which restrict the applicable plasma diagnostics to non-invasive methods with small footprint. So plasma chamber parameters, optical emission spectroscopy (OES), and self-excited electron spectroscopy (SEERS) are used to characterize the plasma and to understand chamber wall conditioning effects in an Ar plasma. The parameters are classified according to their origin—the region they are representative for. The center ion density is estimated from the DC current and compared to the SEERS electron density reflecting the electron density close to that at the chamber wall. The conditioning effects are caused by Si sputtering at a Si wafer changing the chamber wall state only when the chamber is clean, subsequent plasmas in the same chamber are not affected in that way. Through the combination of the complementary methods it can be shown that the chamber wall condition finally changes the radial plasma density distribution. Also the heating of electrons in the sheath is shown to be influenced by conditioning effects.

SESSION DT2: COMPUTATIONAL PLASMA MODELING

Tuesday Morning, 11 October 2016
Room: 2a at 8:30
Laxminarayan Raja, University of Texas, presiding

Contributed Papers

8:30

DT2 1 Multicomponent Transportmodel for Normal-Pressure Plasmas: Modelling and Numerical Methods JUERGEN GEISER, *Ruhr University of Bochum* We are motivated to model and simulate multicomponent transport models for cold atmospheric plasmas (CAPs). Such problems are related to the atmospheric pressure and room-temperature regimes. The plasmas are weakly ionized and have high relations of radical concentrations, e.g., oxygen, which are important for applications on surface-modifications. We derive a model based on multicomponent plasma regimes, while. each single species influences the flux-characteristics and the characteristic of the mixture, i.e., the diffusive effects of each specie are important. We assume that in the temperature- and pressure-regimes, the particles have small characteristic length instead of the length in the apparatus and we can derive and apply macroscopic equations. We extend the multicomponent systems (plasma-model) with the Stefan-Maxwell (SM) equation instead of a standard Fickian approach, while we assume to deal with non-dominant gaseous species. For solving such delicate nonlinear SM equations, we propose new iterative splitting methods based on the relaxation approaches. The novel solver methods are tested with multicomponent models in the literature.

8:45

DT2 2 Investigating The Role of Temporal Smoothing in Circuit Models for PIC/DSMC Simulations* STAN MOORE, MATTHEW HOPKINS, CHRISTOPHER MOORE, *Sandia National Laboratories* Including a circuit model in PIC/DSMC [1-2] simulations is essential for reproducing realistic electrical breakdown behavior. A commonly used circuit model for 1D simulations was developed by Verboncoeur *et al.* [3]. Because PIC simulations use computational superparticles to represent many physical particles, severe noise in the measured current from particles can result, especially when using small timesteps. In the extreme case of timestep approaching zero, current measured by particles impacting a surface during a timestep becomes ill-defined without smoothing. In this talk, we investigate the effect of a noisy current on Verboncoeur's circuit model and test whether temporally smoothing quantities of interest can help improve the results. We also describe an alternative method of solving the circuit equations and compare to Verboncoeur's method.

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

[1]C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation* (McGraw-Hill, New York, 2005).
[2]G. A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows* (Oxford University Press, Oxford, UK, 1994).
[3]J. P. Verboncoeur, M. V. Alves, V. Vahedi, and C. K. Birdsall, J. Comp. Phys. **104**, 321 (1993).

9:00

DT2 3 Semi-analytical description of arbitrary electron energy distribution function for non-kinetic models WLADISLAW DOBRYGIN, OLIVER SCHMIDT, *Dep. for Functional Materials and Coating Technologies, Robert Bosch GmbH, D-70465 Stuttgart, Germany* RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Germany* An efficient way to study chemistry and fundamental processes of plasmas is a global (volume averaged) chemical model. The process conditions (absorbed power, pressure), the plasma chemistry and the shape of electron energy distribution function (EEDF) are the crucial model input parameters. Langmuir probe measurements of EEDF in very well-known reactors like ICP shows non-maxwellian distributions [1]. In order to solve the global models of this kind of plasmas without solving a Boltzmann-equation, the EEDF with parametric mean energy have to be described by an analytic function (i.e. Maxwell- or Druyvesteyn distribution). If the EEDF has a convex shape, Druyvesteyn-like distributions with modified exponent x can be used [2] but others such as the bi-Maxwellian distribution cannot. In this work, we show a way to represent an arbitrary EEDF using a semi-analytical function which allows us to variate the mean energy of the EEDF. The EEDF shape is given from Langmuir probe measurement. The validation will be shown in calculations of low pressure ICP discharge in Argon and Acetylene chemistry.

[1]V. A. Godyak *et al.*, Plasma Sources Sci. Technol. **11**, 525 (2002).
[2]J. T. Gudmundsson, Plasma Sources Sci. Technol. **10**, 76 (2001).

9:15

DT2 4 Effect of a momentum-transfer scattering at inelastic collisions on the electron transport II: Case study in Ar NAOHIKO SHIMURA, TAKASHI YAGISAWA, *Toshiba Corporation* TOSHIAKI MAKABE, *Keio University* In the previous paper, we presented an expression for the inelastic momentum-transfer scattering on the collision integral of the Boltzmann equation, in order to reflect the effect of an inelastic scattering distribution of an electron with a molecule on the electron kinetics in gases and collisional plasmas [1]. In the present paper we will discuss the influence of the anisotropic scattering of the inelastic collisions on the electron velocity distribution in Ar with a scattering distribution of cosT. The numerical procedure is based on our Direct Numerical Procedure of the Boltzmann equation [2]. A comparison of the electron velocity distribution between of the anisotropic scattering and isotropic one in an rf-field will give us a renewed interest in the electron transport in gases and collisional plasmas.

[1]T. Makabe and R. White, J. Phys. D: Appl. Phys. **48**, 485205 (2015).
[2]T. Makabe and Z. Petrovic, *Plasma Electronics*, 2nd ed. (CRC Press, 2015).

9:30

DT2 5 Validation and Verification of Two Particle-In-Cells Codes for a Glow Discharge ALEXANDER KHRABROV, JOHAN CARLSSON, IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory* TIMOTHY SOMMERER, *GE Global Research* Two PIC codes, a research code EDIPIC and a commercial LSP, were benchmarked and validated for a parallel-plate glow discharge in helium, in which the axial electric field profile had been carefully mapped in experiment [1]. Both codes reproduce very well the cathode fall and the negative glow regions of the discharge, including formation of high density plasma with very low-energy (0.1 eV) electrons in the negative glow. A detailed comparison was performed for several synthetic cases of electron-beam injection into helium gas and showed that the codes are in excellent agreement for ionization rate, as well as for collisional transport if isotropic scattering was assumed. However, the electron velocity distribution is anisotropic in the cathode fall; hence an adequate model of anisotropic scattering in elastic/inelastic collisions needs to be adopted. Because of the experimental uncertainty for the emission yield, it is tuned to make the cathode current computed by each code match the experimental values. The resulting computed electric fields are in excellent agreement with each other and within about 10% of the experimental value. In the process of validation, several issues with each of the codes were noted and addressed, including the necessity to use quality random number generators, and, for the commercial code, updating the field solver, the secondary electron emission, and the external circuit algorithms.

[1]E. A. den Hartog, D. A. Doughty, and J. E. Lawler, Phys. Rev. A **38**, 2471 (1988).

9:45

DT2 6 Incorporation of the electron energy equation into the hybrid Monte Carlo - fluid model for glow discharge: the applicability and reliability of the model ENDER EYLENCEOGLU, ISMAIL RAFATOV, *Middle East Technical University, Ankara, Turkey* ANATOLY KUDRYAVTSEV, *Saint Petersburg State University, St.Petersburg, Russia* A modification of the conventional hybrid Monte Carlo - fluid model for glow discharge, which incorporates the electron energy equation, is considered. In the proposed model electrons are separated into two groups, namely, high energetic fast and low energetic slow (bulk) electrons. Density profiles of ions, slow electrons, and meta-stable particles are determined from the solution of corresponding continuity equations. Fast electrons, which are responsible for ionization and excitation events in the discharge, are simulated by the Monte-Carlo method. The temperature profile for slow electrons is obtained from the solution of the energy balance equation. The transport (mobility and diffusion) coefficients as well as the reaction rates for slow electrons are determined as functions of the electron temperature. Test calculations are carried out for the direct current glow discharge in argon within two-dimensional geometry. Comparison of the computed results with those obtained from the conventional fluid and hybrid models and the experimental data is done, the applicability and reliability of the proposed model is studied in details.

10:00

DT2 7 plasmaFoam: An OpenFOAM framework for computational plasma physics and chemistry AYYASWAMY VENKATTRAMAN, ABHISHEK KUMAR VERMA, *University of California Merced* As emphasized in the 2012 Roadmap for low temperature plasmas (LTP), scientific computing has emerged as an essential tool for the investigation and prediction of the fundamental physical and chemical processes associated with these systems. While several in-house and commercial codes exist, with each having its own advantages and disadvantages, a common framework that can be developed by researchers from all over the world will likely accelerate the impact of computational studies on advances in low-temperature plasma physics and chemistry. In this regard, we present a finite volume computational toolbox to perform high-fidelity simulations of LTP systems. This framework, primarily based on the OpenFOAM solver suite, allows us to enhance our understanding of multiscale plasma phenomenon by performing massively parallel, three-dimensional simulations on unstructured meshes using well-established high performance computing tools that are widely used in the computational fluid dynamics community. In this talk, we will present preliminary results obtained using the OpenFOAM-based solver suite with benchmark three-dimensional simulations of microplasma devices including both dielectric and plasma regions. We will also discuss the future outlook for the solver suite.

10:15

DT2 8 Particle in Cell/Monte Carlo Collision Analysis of the Problem of Identification of Impurities in Gas within the Plasma Electron Spectroscopy Method CEMRE KUSOGLU SARIKAYA, ISMAIL RAFATOV, *Middle East Technical University* ANATOLY KUDRYAVTSEV, *Saint Petersburg State University* Particle in Cell/Monte Carlo Collision (PIC/MCC) analysis of the problem of identification of impurities in gas within the Plasma Electron Spectroscopy (PLES) method is carried out. The idea of the PLES is based on the analysis of the effect on the EEDF due to electrons, released in the Penning reactions between the metastable atoms of working gas and impurity. $1d3v$ PIC/MCC numerical code is developed and verified under the conditions of RF capacitively coupled discharge in helium. The efficiency of the code was increased by its parallelization using Open MPI. Test calculations showed that the efficiency of the code increases about 70 times with increase of the number of cores up to 95. Simulations have been done for DC glow discharge in helium doped by the small amount of argon. The elastic, excitation and ionization collisions between electron-neutral pairs and isotropic scattering and charge exchange collisions between ion-neutral pairs and Penning ionizations are taken into account. PIC/MCC numerical model is incorporated with equations for density of the metastable helium atoms in the fluid approximation. Numerical results are consistent well with the theoretical analysis of formation of nonlocal EEDF and existing experimental data.

SESSION DT3: CHEMICAL KINETICS/COMBUSTION & ENVIRONMENTAL

Tuesday Morning, 11 October 2016
Room: 2b at 8:30
R. Engeln, Technische Universiteit Eindhoven, presiding

Contributed Papers

8:30

DT3 1 Experimental Investigation of Pulsed Nanosecond Streamer Discharges for CO_2 Reforming MICHAEL PACHUILO, DIMA LEVKO, LAXMINARAYAN RAJA, PHILIP VARGHESE, *The University of Texas at Austin* Rapid global industrialization has led to an increase in atmospheric greenhouse gases, specifically carbon dioxide levels. Plasmas present a great potential for efficient reforming of greenhouse gases. There are several plasma discharges which have been reported for reforming process: dielectric barrier discharges (DBD), microwave discharges, and glide-arcs. Microwave discharges have CO_2 conversion energy efficiency of up to 40% at atmospheric conditions, while glide-arcs have 43% and DBD 2-10%. In our study, we analyze a single nanosecond pulsed cathode directed streamer discharge in CO_2 at atmospheric pressure and temperature. We have conducted time resolved imaging with spectral bandpass filters of a streamer discharge with an applied negative polarity pulse. The image sequences have been correlated to the applied voltage and current pulses. From the spectral filters we can determine where spatially and temporally excited species are formed. In this talk we report on spectroscopic studies of the discharge and estimate plasma properties such as temperature and density of excited species and electrons. Furthermore, we report on the effects of pulse polarity as well as anodic streamer discharges on the CO_2 conversion efficiency. Finally, we will focus on the effects of vibrational excitation on carbon dioxide reforming efficiency for streamer discharges. Our experimental results will be compared with an accompanying plasma computational model studies.

8:45

DT3 2 Plasma assisted ignition with nanosecond surface dielectric barrier discharge. Two modes of nanosecond surface discharge SERGEY SHCHERBANEV, *Ecole Polytechnique, Paris* NIKOLAY POPOV, *Skobeltsyn institute of nuclear physics, Moscow State University (MSU), Moscow* SVETLANA STARIKOVSKAIA, *Laboratory of Plasma Physics, Ecole Polytechnique, Paris* LPP TEAM, LIA FRANCE-RUSSIA COLLABORATION Nanosecond surface dielectric barrier discharge (nSDBD) is an efficient tool for a multi-point plasma-assisted ignition of combustible mixtures at elevated pressures. In combustible mixtures, nSDBD initiates numerous combustion waves propagating from the electrode. This work presents a comparative experimental study of the surface dielectric barrier discharge initiated by high voltage pulses ($U = \pm(20\text{-}60)$ kV) of different polarities in air at elevated pressures ($P=1-12$ bar). Discharge morphology, deposited energy, and spectroscopy of the discharges are analyzed. Differences between the discharges of the different polarity, as well as the changes in the discharge morphology with changing of a gas mixture composition, are discussed. The initiation of combustion with nSDBD was studied experimentally at high initial pressures up to 6 bar on the example of lean H_2/Air. The ignition is initiated with two different discharge modes: streamer and filamentary. The influence of the discharge structure and energy deposition on the ignition is demonstrated. Three regimes of multi-point ignition were observed: ignition with a few kernels, quasi-uniform ignition along the edge of high voltage electrodes and ignition along the plasma channels.

9:00

DT3 3 Green technology for conversion of renewable hydrocarbon based on plasma-catalytic approach IGOR FEDIRCHYK, OLEG NEDYBALIUK, VALERIY CHERNYAK, *Taras Shevchenko National University of Kyiv* VALENTINA DEMCHINA, *Gas Institute of National Academy of Sciences of Ukraine* The ability to convert renewable biomass into fuels and chemicals is one of the most important steps on our path to green technology and sustainable development. However, the complex composition of biomass poses a major problem for established conversion technologies. The high temperature of thermochemical biomass conversion often leads to the appearance of undesirable byproducts and waste. The catalytic conversion has reduced yield and feedstock range. Plasma-catalytic reforming technology opens a new path for biomass conversion by replacing feedstock-specific catalysts with free radicals generated in the plasma. We studied the plasma-catalytic conversion of several renewable hydrocarbons using the air plasma created by rotating gliding discharge. We found that plasma-catalytic hydrocarbon conversion can be conducted at significantly lower temperatures (500 K) than during the thermochemical (≈ 1000 K) and catalytic (800 K) conversion. By using gas chromatography, we determined conversion products and found that conversion efficiency of plasma-catalytic conversion reaches over 85%. We used obtained data to determine the energy yield of hydrogen in case of plasma-catalytic reforming of ethanol and compared it with other plasma-based hydrogen-generating systems.

9:15

DT3 4 Enhancement of NO_x and hydrocarbon conversion in plasma-activated catalysis BILL GRAHAM, WAHMEED ADRESS, *Centre for Plasma Physics* ALEXANDRE GOGUET, HUI YANG, FABIO DE ROSA, CHRISTOPHER HARDACRE, CRISTINA STERE, *CenTACat, Queen's University Belfast, N. Ireland, U.K* Atmospheric pressure, non-thermal plasma-activated-catalysis is showing real promise in a number of applications. Here we report on how electrical, visible and FTIR spectroscopy and mass spectroscopy measurements in a kHz atmospheric pressure He plasma jet coupled with a Ag/Al_2O_3 catalyst allowed us produce and confirm a strong enhancement of both NO_x and hydrocarbon conversion at a measured gas temperature of $\leqslant 250\,°C$ [1]. How these and other measurements have provided an insight into the fundamental physical and chemical processes in the plasma environment that have helped us move to a more efficient system and other processes will be discussed.

[1]C. E. Stere, W. Adress, R. Burch, S. Chansai, A. Goguet, W. G. Graham, F. De Rosa, V. Palma, and C. Hardacre, ACS Catalysis **4**, 666 (2014).

9:30

DT3 5 Conversion of CO_2 to CO using radio-frequency atmospheric pressure plasmas ALEXANDER FOOTE, JAMES DEDRICK, DEBORAH O'CONNELL, MICHAEL NORTH, TIMO GANS, *University of York* Low temperature plasmas can be used for the in situ generation of CO, from relatively non-toxic CO_2. CO is very useful in many industrial chemical processes and so, via low temperature plasmas, CO_2, a waste product, can be converted into a valuable chemical. The key challenges in using this method, for CO production, are optimising the energy efficiency, maximising the conversion of CO_2 into CO and then separating the CO from the other species produced in the plasma. Very high yields of CO, greater than 90%, have been achieved at atmospheric pressure using argon as a carrier gas with admixtures up to 1.5% with energy efficiencies of up to 4%. The plasma generated in continuous and spatially homogeneous and is driven at a frequency of 40.68 MHz. A zero dimensional global model has also been used to simulate the chemical kinetics of the plasma to determine the dominant dissociation processes and is in good agreement with the experimentally determined yields. The model is used to determine how important a role the vibrational states of CO_2 are, in a highly collisional plasma, to the production of CO and there can provide insight into how to improve the energy efficiency and suppress unwanted reactions.

9:45

DT3 6 Study of nanosecond discharges in different H_2 air mixtures at atmospheric pressure for plasma-assisted applications* ANNE BOURDON, SUMIRE KOBAYASHI, *LPP, UMR 7648, Ecole Polytechnique, route de Saclay, 91128 Palaiseau Cedex, France* ZDENEK BONAVENTURA, *Department of Physical Electronics, Faculty of Science, Masaryk University, Brno, Czech Republic* FABIEN THOLIN, *ONERA, DMPH Department, 29 avenue de la Division Leclerc, 92322 Châtillon cedex, France* NIKOLAY POPOV, *Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Leninskie gory, Moscow 119991, Russia* This paper presents 2D simulations of nanosecond pulsed discharges between two point electrodes in different H_2/air mixtures and in air at atmospheric pressure. A fluid model is coupled with detailed kinetic schemes for air and different H_2/air mixtures to simulate the discharge dynamics. First, as the positive and negative ionization waves propagate in the interelectrode gap, it has been observed that in H_2/air mixtures with equivalence ratios between 0.3 and 2, major positive ions produced by the nanosecond discharge are N_2^+, O_2^+ and HN_2^+. The discharge dynamics is shown to vary only slightly for equivalence ratios of the H_2/air mixture between 0.3 and 2. Then, as the discharge transits to a nanosecond spark discharge, we have studied the different chemical reactions that lead to fast gas heating and to the production of radicals, as O,H and OH. Both thermal and chemical effects of the nanosecond spark discharge are of interest for plasma assisted combustion applications.

*This work has been supported by the project DRACO (Grant No. ANR-13-IS09-0004) and the french russian LIA Kappa.

Invited Papers

10:00

DT3 7 Non-equilibrium kinetics of plasma-assisted combustion: the role of electronically excited atoms and molecules*

NIKOLAY POPOV, *Moscow State University*

A review of experimental and theoretical investigations of the effect of electronically excited atoms and molecules on the induction delay time and on the shift of the ignition temperature threshold of combustible mixtures is presented. At relatively low initial gas temperature, the effect of excited $O(^1D)$ atoms on the oxidation and reforming of combustible mixtures is quite significant due to the high rates of reactions of $O(^1D)$ atoms with hydrogen and hydrocarbon molecules. The singlet oxygen molecules, $O_2(a^1\Delta_g)$, participate both in chain initiation and chain branching reactions, but the effect of $O_2(a^1\Delta_g)$ in the ignition processes is generally less important compared to the oxygen atoms. To reduce the ignition delay time and decrease the temperature threshold of fuel-air mixtures, the use of gas discharges with relatively high E/N values is recommended. In this case the reactions of electronically excited $N_2(A^3\Sigma_u^+, B^3\pi_g, C^3\pi_u, a'^1\Sigma_u^-)$ molecules, and atomic particles in ground and electronically excited states are extremely important. The energy stored in electronic excitation of atoms and molecules is spent on the additional dissociation of oxygen and fuel molecules, on the fast gas heating, and finally to the triggering of chain branching reactions.

*This work was partially supported by AOARD AFOSR, FA2386-13-1-4064 grant and Linked International Laboratory LIA KaPPA (France-Russia).

TUESDAY MORNING \ DT3

SESSION ET1: NEGATIVE ION COMPLEX, AND DUST PARTICLE CONTAINING PLASMAS

Tuesday Morning, 11 October 2016
Room: 1 at 11:00
Uwe Kortshagen, University of Minnesota, presiding

Contributed Papers

11:00

ET1 1 Plasma separation: physical separation at the molecular level RENAUD GUEROULT, *LAPLACE, CNRS* JEAN-MARCEL RAX, *LOA, CNRS* NATHANIEL J. FISCH, *PPPL* Separation techniques are usually divided in two categories depending on the nature of the discriminating property: chemical or physical. Further to this difference, physical and chemical techniques differ in that chemical separation typically occurs at the molecular level, while physical separation techniques commonly operate at the macroscopic scale. Separation based on physical properties can in principle be realized at the molecular or even atomic scale by ionizing the mixture. This is in essence plasma based separation. Due to this fundamental difference, plasma based separation stands out from other separation techniques, and features unique properties. In particular, plasma separation allows separating different elements or chemical compounds based on physical properties. This could prove extremely valuable to separate macroscopically homogeneous mixtures made of substances of similar chemical formulation. Yet, the realization of plasma separation techniques' full potential requires identifying and controlling basic mechanisms in complex plasmas which exhibit suitable separation properties. In this paper, we uncover the potential of plasma separation for various applications, and identify the key physics mechanisms upon which hinges the development of these techniques.

11:15

ET1 2 Effect of the gas temperature and pressure on the nucleation time of particles in low pressure Ar-C_2H_2 rf plasmas JIASHU LIN, *Kyoto Institute of Technology* MARIE HENAULT, *Université d'Orléans/GREMI* SAGI ORAZBAYEV, *Al Farabi Kazakh National University* LAÏA BOUFENDI, *Université d'Orléans/GREMI* KAZUO TAKAHASHI, *Kyoto Institute of Technology* AL FARABI KAZAKH NATIONAL UNIVERSITY COLLABORATION, KYOTO INSTITUTE OF TECHNOLOGY TEAM, GREMI TEAM Particle formation in low pressure plasmas is a 3-step process. The first one corresponds to the nucleation and growth of nano-crystallites by ion-molecular reactions, the agglomeration phase to form large particles, and the growth by radical deposition on the particle surface. The nucleation phase was demonstrated to be sensitive to gas temperature and pressure. In this work, time of nucleation phase of particles formation in low pressure cold rf C_2H_2/Ar plasmas studied by varying gas temperature from 265 K to 375 K, gas pressure from 0.4 mbar to 0.8 mbar and rf power from 6 W to 20 W. The ratio of C_2H_2/Ar is fixed to 2/98 in terms of pressure. Several previous works reported that particle formation takes a few sec at room temperature in C_2H_2 plasmas and the time is much shorter than 0.1 s in SiH_4 plasmas. Time evolution of self-bias voltage was mainly used to determine nucleation time. The self-bias voltage was modified by phase transition between the steps from nucleation to coagulation. The experimental results showed that the nucleation time increased with gas temperature, decreased with gas pressure and discharge power. At constant gas pressure of 0.4 mbar and discharge power of 6 W, for example, the nucleation time increased from 5 sec to 30 sec with increas

11:30

ET1 3 Dynamic of microparticles in vacuum breakdown BENJAMIN SEZNEC, *LPGP UMR 8578, CNRS, Univ. Paris-Sud, Orsay, Fance* PHILIPPE DESSANTE, *Geeps, , UMR 8507, CNRS, CentraleSupelec, gif, france* TOBIAS JAEGER, LISE CAILLAULT, *LPGP UMR 8578, CNRS, Univ. Paris-Sud, Orsay, Fance* PHILIPPE TESTE, *Geeps, UMR 8507, CNRS, CentraleSupelec, gif, france* TIBERIU MINEA, *LPGP UMR 8578, CNRS, Univ. Paris-Sud, Orsay, Fance* Numerous applications, such as X-ray tubes or particle accelerators, use vacuum as of high voltage isolator. Their performance is limited by the risk of unpredictable breakdown events between electrodes. Moreover, the breakdown usually leads to the formation of arc discharges, which can damage the electrodes. This research aims to give a better description of the origin of the vacuum breakdown. One assumption considers the effect induced by the transport of micro-particles (MP) in the inter-electrodes gap. After their release from hot spots at the anode, MP are exposed to an intense field ~1-5 MV/m, and are bombarded by electrons released from the cathode micro-tips. These electrons can change the MP charge and can lead to partially/completely vaporization of the MP. The model OFEN (Orsay Field Emission Nanoparticles) developed at LPGP describes the MP transport in the inter-electrodes gap and the interactions (heating and modification of the MP charge) between electrons and the MP. The results clearly show four regimes of MP trajectories obtained for different emission currents, MP sizes and inter-electrode distances and the effect of the MP crash on the cathode.

11:45

ET1 4 New radio-frequency setup for studying large 2D complex plasma crystals VLADIMIR NOSENKO, JOHN MEYER, HUBERTUS THOMAS, *German Aerospace Center DLR, Research Group on Complex Plasmas* There is a growing body of evidence that many properties of complex plasmas, such as thermal conductivity and diffusion coefficient may be system-size dependent. To test this assumption, experiments are needed where the size of a complex plasma can be varied in a wide range. So far, the existing experimental setups (based on various modifications of the GEC rf reference cell) allowed the maximum size of a good-quality 2D plasma crystal of about 6-7 cm. To obtain a much larger uniform 2D plasma crystal, a larger setup is necessary. In this presentation, we report on the new radio-frequency setup that has been built and is now operational in the Research Group on Complex Plasmas. It is based on a relatively large (90 cm in diameter) vacuum chamber where a radio-frequency discharge is used to levitate dust particles. The discharge is created between the lower rf electrode and the grounded chamber walls, the particles levitate in the plasma (pre)sheath above the electrode and are observed through the large top glass window and through the side windows. The first observations of plasma crystals in the new setup will be reported.

12:00

ET1 5 Charging of particles on a surface LUCAS HEIJMANS, SANDER NIJDAM, *Eindhoven University of Technology* This contribution focusses on the seemingly easy problem of the charging of micrometer sized particles on a substrate in a plasma. This seems trivial, because much is known about both the charging of surfaces near a plasma and of particles in the plasma bulk. The problem, however, becomes much more complicated when the particle is on the substrate surface. The charging currents to the particle are then highly altered by the substrate plasma sheath. Currently there is no consensus in literature about the resulting particle charge. We shall present both experimental measurements and numerical simulations of the charge on these particles. The experimental results are acquired by measuring the particle acceleration in an external electric field. For the simulations we have used our specially developed model. We shall compare these results to other estimates found in literature.

12:15

ET1 6 Numerical Analysis on Size Dependency of Particulate Matter Behavior in Electric Collector YOSUKE SATO, AKIO UI, *Mechanical Systems Laboratory, Corporate Research and Development Center, Toshiba Corporation, 1 Komukai-Toshiba-Cho, Saiwai-ku, Kawasaki 212-8582* Recently the adverse effect of particulate matter having aerodynamic diameters (AD) of less than 2.5μm (PM2.5) on the human body has been attracted a lot of attention and it is expected to increase concerns about the effect of smaller particles, namely particulate matter having AD of less than 0.1μm (PM0.1). For air purifiers it is important to have the ability of efficiently collecting these particulate matters. In this work attention is paid to a plasma electric collector which utilizes Coulomb's force and is suitable to collect relatively small particles. Numerical simulations of plasma characteristics including two charging mechanism and tracking of charged particles are used to evaluate charging and collecting properties of the particles. Charge number attached on each particle decreased with decreasing AD and the number attached on each 0.1μm particle is one-by-hundredth to that of 2.5μm particle. However, the results of simulation on tracking of charged particles show that the collecting efficiency of 0.1μm particles is higher than that of 2.5μm particles. This is expected due to the fact that the dependencies of external forces (Coulomb's, gravitational and aerodynamic drag) on the AD differ from each other. Detail results will be shown during presentation.

SESSION ET2: SHEATHS/PLASMA PHYSICS

Tuesday Morning, 11 October 2016
Room: 2a at 11:00
Benjamin Yee, Sandia National Laboratories, presiding

Contributed Papers

11:00

ET2 1 Formation of Anode Spots in Low Pressure Plasmas* BRETT SCHEINER, *Univ of Iowa* EDWARD BARNAT, MATTHEW HOPKINS, *Sandia National Laboratories* SCOTT BAALRUD, *Univ of Iowa* BENJAMIN YEE, *Sandia National Laboratories* When small electrodes are biased sufficiently above the plasma potential, the rate of electron impact ionization of neutrals can increase near the electrode. At neutral gas pressures of $\sim$1-100mTorr, it has been previously observed that if this ionization rate is sufficiently high a double layer forms near the electrode. Sometimes this double layer will move outward, separating a high potential plasma, attached to the electrode surface, from the bulk plasma. This phenomenon is known as an anode spot or fireball. Using observations from the first 2D particle-in-cell simulations of the anode spot, a model has been developed describing this formation process. In this model ionization leads to the buildup of an ion rich region adjacent to the electrode, which modifies the potential structure in a way that traps electrons near the electrode surface. This establishes a quasineutral plasma near the electrode. When the density of this plasma is large enough, a pressure imbalance across the double layer leads to its expansion from the electrode surface. Observations from simulations, along with the presented model, are found to be consistent with time resolved measurements of the electron density from laser collision induced fluorescence, and with plasma emission measurements.

*This research was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under contract DE-AC04-94SL85000 and by the Office of Science Graduate Student Research (SCGSR) program under Contract Number DE-AC05-06OR23100.

Invited Papers

11:15

ET2 2 First experimental studies of ion flow in 3 ion species plasmas at the presheath-sheath transition*
GREG SEVERN, *Dept. of Physics & Biophysics, University of San Diego*

The Bohm sheath criterion is studied with laser-induced fluorescence (LIF) in three ion species plasmas using two tunable diode lasers. KrI or HeI is added to a low pressure unmagnetized dc hot filament discharge in a mixture of argon and xenon gas confined by surface multi-dipole magnetic fields. The argon and xenon ion velocity distribution functions are measured at the sheath-presheath boundary near a negatively biased boundary plate. The potential structures of the plasma sheath and presheath are measured by an emissive probe. Results are compared with previous experiments with Ar–Xe plasmas, where the two ion species were observed to reach the sheath edge at nearly the same speed. This speed was the ion sound speed of the system, which is consistent with the generalized Bohm criterion. In such two ion species plasmas instability enhanced collisional friction (IEF) was demonstrated [1] to exist which accounted for the observed results. When three ion species are present, it is demonstrated under most circumstances the ions do not fall out of the plasma at their individual Bohm velocities. It is also shown that under most circumstances the ions do not fall out of the plasma at the system sound speed. Results are consistent with the presence of instabilities. Author gratefully acknowledges collaborators Dr. Noah Hershkowtiz, Dr. Chi-Shung Yip, Dept. of Engineering Physics, Univ. Wisconsin-Madison, and Dr. Scott Baalrud, Dept. Physics, Univ. Iowa.

*Thanks to US DOE, grant DE-SC00014226.

[1]Yip *et al.*, Phys. Plasmas (2010).

Contributed Papers

11:45

ET2 3 Observation of Ion-neutral Collision Effect on Two-Ion-Stream Instability near Sheath-Presheath Boundary NAM-KYUN KIM, J. SONG, H.-J. ROH, Y. JANG, S. RYU, G.-H. KIM, *Seoul National University, Seoul, Korea* The ion velocity normal to the sheath-presheath boundary in weakly-collisional Ar/Xe mixture plasmas was measured by using LIF measurement. This investigation would give an answer to the old debate topic in the sheath community, whether each ion enters the sheath with their *own Bohm velocity*, $C_B = (T_e/M_i)^{1/2}$. In collisionless two-ion-species plasmas, Barrud and Hershkowitz concluded that the two-stream instability limits their velocities to become *the common system sound speed*, $C_s = (n_1 T_e/n_e M_1 + n_2 T_e/n_e M_2)^{1/2}$. This instability is activated when the relative velocity becomes a critical velocity. In practices, the collisionless condition is not achievable. In this study, the ion-neutral collision effect on the instability was investigated with increasing the pressure of the Ar/Xe mixture gas in the range of 0.5 - 2 mTorr. Plasma is generated in a DC multi-dipole source in which $n(Ar^+)/n(Xe^+)$ is controlled to be 1. Results show that the instability is grown at $p < 2$ mTorr and the ion drift velocities at the sheath edge are close to C_s. At 2 mTorr, the ions reach their individual C_B at the sheath edge because the instability is not grown, observing that the characteristic length of the instability is a function of the ion-neutral collisions. The details will be discussed in the conference.

12:00

ET2 4 Boundary conditions for electropositive and electronegative radio-frequency sheaths MARK SOBOLEWSKI, *National Institute of Standards and Technology* Plasma sheaths play a dominant role in determining ion bombardment energies. To optimize plasma processes, sheaths must be understood and carefully controlled, which requires predictive models. One very efficient approach is to only model the sheath, excluding the bulk plasma. This approach, however, requires boundary conditions at the plasma/sheath boundary. Models that use the step approximation for electron density require initial ion velocities. More exact models with Boltzmann electrons (and, for electronegative discharges, negative ions) require the electron temperature (and the temperature and relative density of negative ions). It is often assumed that these boundary conditions have negligible effects on ion energies, but, for certain conditions in radio-frequency sheaths, this is not true. Analytic models as well as numerical simulations show that, at low frequencies ($\leqslant$ 1 MHz) and high bias voltages, the amplitude of the low-energy peak in ion energy distributions (IEDs) at the electrode is very sensitive to the boundary conditions. By measuring IEDs and sheath voltage waveforms, we obtain the most appropriate values of the boundary conditions for electropositive (Ar) as well as electronegative (CF_4) discharges and insight into their presheath dynamics.

12:15

ET2 5 Laser-Collisional Induced Fluorescence Measurements of a Magnetosheath in a Biasable Ring Cusp Source NEIL ARTHUR, JOHN FOSTER, *Univ of Michigan - Ann Arbor* This work involves exploring active control of the plasma potential and density spatial distribution in a mulitpole ion source through the active biasing of individual magnetic cusps. Cusp bias can be achieved by applying voltage to the magnetic surface generating the cusp. By controlling the current flow through the cusps, active altering of the primary electron containment length, at least at low voltages, is possible. Electrostatic probes do not work well in the presence of magnetic field and within sheaths. The Laser-Collisional Induced Fluorescence (LCIF) diagnostic is enabling in that it allows for imaging of the electron distribution in the magnetosheath. LCIF is used to quantify the response of electron density to active cusp biasing. We hope to gain insight into the physical processes occurring at the magnetic cusps and elucidate how those processes impact not only the plasma conditions in the bulk plasma, but also source efficiency and stability. The goal is to determine how bulk plasma properties change in response to modifications to current collection at the cusp magnetosheath. If the plasma properties vary with electric field in the cusp, then magnetic cusps must be considered as active rather than passive collectors.

SESSION ET3: PLASMA LIQUID INTERACTIONS
Tuesday Morning, 11 October 2016; Room: 2b at 11:00;

Invited Papers

11:00

ET3 1 Control of Reactive Species Generated by Low-frequency Biased Nanosecond Pulse Discharge in Atmospheric Pressure Plasma Effluent

KEISUKE TAKASHIMA, TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University*

The control of hydroxyl radical and the other gas phase species generation in the ejected gas through air plasma (air plasma effluent) has been experimentally studied, which is a key to extend the range of plasma treatment. Nanosecond pulse discharge is known to produce high reduced electric field (E/N) discharge that leads to efficient generation of the reactive species than conventional low frequency discharge, while the charge-voltage cycle in the low frequency discharge is known to be well-controlled. In this study, the nanosecond pulse discharge biased with AC low frequency high voltage is used to take advantages of these discharges, which allows us to modulate the reactive species composition in the air plasma effluent. The utilization of the gas-liquid interface and the liquid phase chemical reactions between the modulated long-lived reactive species delivered from the air plasma effluent could realize efficient liquid phase chemical reactions leading to short-lived reactive species production far from the air plasma, which is crucial for some plasma agricultural applications.

Contributed Papers

11:30

ET3 2 Chemical reaction by plasma in gas-liquid two-phase flow system MOTONOBU GOTO, KAKERU MANO, YUI HAYASHI, NORIHARU TAKADA, HIDEAKI KANDA, *Nagoya University* Two plasma processes using gasliquid two-phase flow were developed. One is gas/liquid slug flow in capillary glass tube where gas bubbles moved stably in liquid flow. Plasma was generated in bubbles by pulsed bipolar voltage and the liquid phase was mixed by circulated convection due to shearing force. As a gas, air, argon, helium, oxygen, or nitrogen was used. The pulsed bipolar voltage of 10 kV was applied at 10 kHz. The generated plasma was evaluated by ICCD image and high speed camera. The optical emission spectra was analyzed to identify the active species. By using this process, organic compound dissolved in liquid aqueous phase was reacted with oxidation. Another process was creeping plasma on flowing liquid film along glass tube outer surface. Owing to the thin film thickness, organic compound dissolved in liquid phase was reacted effectively. Therefore, effective reaction process could be established in gas/liquid two-phase flow by controlling the gas/liquid flow.

11:45

ET3 3 Plasma charging and electron-based reactions at the plasma-liquid interface of an isolated liquid droplet* PAUL MAGUIRE, CHARLES MAHONY, COLIN KELSEY, DAVID RUTHERFORD, DAVIDE MARIOTTI, *Ulster University* DECLAN DIVER, *University Of Glasgow* The study of plasma-liquid interactions opens up exciting new opportunities for applications but numerous investigative challenges remain. The use of isolated and stable spherical liquid microdroplets in a non-thermal equilibrium atmospheric pressure plasma offers a new platform for experimental and theoretical investigations. Since the droplet assumes floating potential, a high flux of electrons with low net energy (~thermal) becomes fixed and solvated within the first monolayers of the liquid leading to highly reactive and rapid chemical reactions. We observe such reactions, e.g. H_2O_2 and metal nanoparticle formation, at rates that are much higher than reported elsewhere. Since the isolated droplet radius is greater than Debye lengths and mean free paths, we have an opportunity to directly compare, for the first time, long-standing collisional probe theories in this important regime. We measure a lower bound average charge of >1E5 electrons on a 13um droplet. Simulations of unipolar corona charging for this size predict ~1E3 electrons. A Comsol-based drift-diffusion model is currently under development and so far experiment and theory match within ~1 order of magnitude but improvements in measurement technique are in progress.

*Funding from EPSRC acknowledged (Grants EP/K006088/1 and EP/K006142/1).

12:00

ET3 4 Reacting chemistry at the air-water interface* TOMOYUKI MURAKAMI, *Seikei University* THOMAS MORGAN, LUTZ HUWEL, *Wesleyan University* WILLIAM GRAHAM, *Queen's University Belfast* Plasma interaction with gas-liquid interfaces is becoming increasingly important in biological applications, chemical analysis and medicine. It introduces electrons, new ionic species and reactive species and contributes to chemical and electrical self-organization at the interface. To provide insight into the associated physics and chemistry at work in the evolution of the plasma in the air-water interface (AWI), a time-dependent one-dimensional modelling has been developed. The numerical simulation is used to solve the kinetic equations and help identify the important reaction mechanisms and describe the phenomena associated with hundreds of reacting pathways in gas-phase and liquid-phase AWI chemistry.

*This work was partly supported by JSPS KAKENHI Grant Number 16K04998.

12:15

ET3 5 Transient Species in Plasmas Interacting with Liquids S. REUTER, A. SCHMIDT-BLEKER, J. H. VAN HELDEN, H. JABLONOWSKI, J. WINTER, *INP Greifswald e.V.* J. SANTOS SOUSA, *Univ. Paris-Sud, Université Paris-Saclay* M. GIANELLA, G. RITCHIE, *Department of Chemistry, University of Oxford, United Kingdom* K.-D. WELTMANN, *INP Greifswald e.V.* Processes of non-equilibrium plasmas at gas-liquid interfaces are determined by transient species. Quantification of these species in the plasma, gas, or liquid is intricate and requires specific diagnostics. In order to study plasma-liquid interaction processes, novel diagnostic concepts need to be developed combined with simulations that allow an insight into the chemical reaction pathways. Significantly relevant transient species in plasmas operated in ambient air include HO_2 and $O_2(a^1\Delta)$, which are diagnosed in this work. The aim is to link localized transient species with longer living stable species in the gas phase and in the liquid phase. Understanding reaction pathways makes it possible to control the reactive species composition generated by the cold plasmas, and further insight into plasma induced reactivity in condensed matter systems can be gained. The work shows a combination of absorption spectroscopic methods and other diagnostic techniques as well as simple kinetics modeling as a way to control the plasma chemical reactions.

SESSION FT1: OPTICAL EMISSION SPECTROSCOPY
Tuesday Afternoon, 11 October 2016
Room: 1 at 14:00
Hiroshi Akatsuka, Tokyo Institute of Technology, presiding

Contributed Papers

14:00

FT1 1 UV/VUV photon fluxes from cylindrical ICPs at 1 MHz in hydrogen URSEL FANTZ, DAVID RAUNER, *Max-Planck-Institut fuer Plasmaphysik* STEFAN BRIEFI, *UniversitÃ¤t Augsburg* DIRK WUENDERLICH, *Max-Planck-Institut fuer Plasmaphysik* The photon fluxes of molecular hydrogen bands and atomic hydrogen lines in the wavelength range from 120 nm to 300 nm in a cylindrical ICP are quantified by means of VUV emission spectroscopy. The molecular analysis is supported by ro-vibrationally resolved corona models taking into account cascading as well. The latter is of particular importance for the interpretation of the ro-vibrational population of the first electronic state (B-state) in the singlet system resulting in the resonant Lyman band (B-X transition). For the analysis of the atomic lines a collisional radiative model is used in which opacity effects are considered. Optical emission spectroscopy is applied as well, allowing for the comparison of the UV/VUV radiation with the VIS radiation. The latter is also used to deduce the plasma parameters such as the electron density and temperature, the degree of dissociation and the atomic particle flux. Langmuir probe measurements yield spatially resolved measurements and allow for quantification of the ion fluxes. The pressure range from 0.3 Pa to 10 Pa for RF powers up to 1 kW is investigated, revealing that the photon fluxes are comparable to the ion fluxes, both of them about two orders of magnitude smaller than the atomic flux.

14:15

FT1 2 Extreme ultraviolet spectroscopy of low pressure helium microwave driven discharges* SUSANA ESPINHO, EDGAR FELIZARDO, ELENA TATAROVA, LUIS LEMOS ALVES, *Instituto de Plasmas e Fusao Nuclear, Instituto Superior Tecnico, Universidade de Lisboa, Portugal* Surface wave driven discharges are reliable plasma sources that can produce high levels of vacuum and extreme ultraviolet radiation (VUV and EUV). The richness of the emission spectrum makes this type of discharge a possible alternative source in EUV/VUV radiation assisted applications. However, due to challenging experimental requirements, publications concerning EUV radiation emitted by microwave plasmas are scarce and a deeper understanding of the main mechanisms governing the emission of radiation in this spectral range is required. To this end, the EUV radiation emitted by helium microwave driven plasmas operating at 2.45 GHz has been studied for low pressure conditions. Spectral lines from excited helium atoms and ions were detected via emission spectroscopy in the EUV/VUV regions. Novel data concerning the spectral lines observed in the 23 - 33 nm wavelength range and their intensity behaviour with variation of the discharge operational conditions are presented. The intensity of all the spectral emissions strongly increases with the microwave power delivered to the plasma up to 400 W. Furthermore, the intensity of all the ion spectral emissions in the EUV range decreases by nearly one order of magnitude as the pressure was raised from 0.2 to 0.5 mbar.

*Work funded by FCT - Fundacao para a Ciencia e a Tecnologia, under Project UID/FIS/50010/2013 and grant SFRH/BD/52412/2013 (PD-F APPLAuSE).

14:30

FT1 3 A computationally assisted spectroscopic technique to measure secondary electron emission coefficients in technological rf plasmas BIRK BERGER, JULIAN SCHULZE, *Department of Physics, West Virginia University; Institute for Electrical Engineering, Ruhr-University Bochum* MANASWI DAKSHA, EDMUND SCHUENGEL, MARK KOEPKE, *Department of Physics, West Virginia University* IHOR KOROLOV, ARANKA DERZSI, ZOLTAN DONKO, *Hungarian Academy of Sciences* A Computationally Assisted Spectroscopic Technique to measure secondary electron emission coefficients (y-CAST) in capacitive rf plasmas is proposed. This non-intrusive, sensitive diagnostic is based on a combination of Phase Resolved Optical Emission Spectroscopy and PIC simulations. Under most conditions in electropositive plasmas the spatio-temporally resolved electron-impact excitation rate features two distinct maxima adjacent to each electrode at different times within one rf period. One maximum is the consequence of an energy gain of the electrons due to sheath expansion. The second maximum is produced by electrons accelerated towards the plasma bulk by the sheath electric field at the time of maximum voltage drop across the sheath. Due to the different excitation mechanisms the ratio of the intensities of these maxima is very sensitive to y, which allows for its determination via comparing the experimentally measured excitation profiles with corresponding simulation data obtained with various y-coefficients. This diagnostic is tested here in a geometrically symmetric reactor, for stainless steel electrodes and argon gas. An effective secondary electron emission coefficient of y = 0.067+-0.010 is obtained, which is in excellent agreement with previous experimental results.

14:45

FT1 4 Actinometry of O, N and F atoms* ANDREY VOLYNETS, *Dept of Physics, Lomonosov Moscow State Univ, Russian Federation* DMITRY LOPAEV, *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State Univ, Russia* ALEXEY ZOTOVICH, *Dept of Physics, Lomonosov Moscow State Univ., Russian Federation* SERGEY ZYRYANOV, *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State Univ. Russia* ALEXANDER RAKHIMOV, *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State Univ, Russia* Actinometry is optical non-invasive diagnostics which is often applied for measurements of atom concentrations in various plasmas. However, it's accuracy relies on knowledge of both apparent excitation cross sections and electron energy distribution function in plasma. Applicability and accuracy of this method for measuring the absolute concentrations of O, N and F atoms in discharge plasma was studied. For this purpose, concentrations of the atoms produced in ICP discharge were measured by two methods: actinometry and appearance potential mass-spectrometry (APMS). Comparison of the results showed good agreement between both methods in a range of experimental errors for oxygen. Since the excitation cross sections for $O(3p^3P)$ and $O(3p^5P)$ states (most often used in actinometry of atomic oxygen) are well known and experimentally validated, the influence of the EEDF shape was accurately evaluated. Following this approach, the theoretical excitation cross sections of $N(3p^4P^o)$, $F(3p^2P^o)$ and $F(3p^4D^o)$ states (used for actinometry of N and F atoms) were absolutely calibrated at first time by fitting the actinometry results to that of APMS.

*This research is supported by Russian Science Foundation (RSF) Grant 14-12-01012.

15:00

FT1 5 Challenges in Optical Emission Spectroscopy* SARAH SIEPA, *FeP/TEF14, Robert Bosch GmbH, Germany* BIRK BERGER, JULIAN SCHULZE, *Department of Physics, West Virginia University, USA, Institute for Electrical Engineering, Ruhr-University Bochum, Germany* EDMUND SCHUENGEL, *Department of Physics, West Virginia University, USA* ACHIM VON KEUDELL, *Institute for Experimental Physics II, Ruhr-University Bochum, Germany* Collisional-radiative models (CRMs) are widely used to investigate plasma properties such as electron density, electron temperature and the form of the electron energy distribution function. In this work an extensive CRM for argon is presented, which models 30 excited states and various kinds of processes including electron impact excitation/de-excitation, radiation and radiation trapping. The CRM is evaluated in several test cases, i.e. inductively and capacitively coupled plasmas at various pressures, powers/voltages and gas admixtures. Deviations are found between modelled and measured spectra. The escape factor as a means of describing radiation trapping is discussed as well as the cross section data for electron impact processes.

*This work was supported by the Ruhr University Research School PLUS, funded by Germany's Excellence Initiative [DFG GSC 98/3].

15:15

FT1 6 Plasma monitoring of nanoparticles formation in SiH4/H2 discharges GIANNIS ALEXIOU, GIANNIS TSIGARAS, ELEFTHERIOS AMANATIDES, DIMITRIOS MATARAS, *Plasma Technology Laboratory - Department of Chemical Engineering - University of Patras* PLASMA TECHNOLOGY LABORATORY - DEPARTMENT OF CHEMICAL ENGINEERING - UNIVERSITY OF PATRAS TEAM Radio-frequency SiH4/H2 discharges is the most common technique for the growth of silicon thin films. Nanoparticles formation and uncontrollable agglomeration to dust is common drawback of such type of discharges due to the extensive reactivity of the species produced in the gas phase. In this work, we deposited silicon films in different plasma conditions while monitoring at the same time nanoparticles formation. The experiments were performed under Continuous Wave (CW) and Pulsed Plasma generation in order to control particles formation. Different time-resolved plasma diagnostics, such as Optical Emission Imaging, Laser Light Scattering and self-bias voltage (Vdc) measurements were used for the detection of particles. Mass spectrometry was also used to record higher silanes formation during the deposition. The deposited films were characterized in terms of crystallinity, hydrogen content and optical properties by Laser Raman, Fourier Transformed Infrared and UV/Vis spectroscopy. Finally, Atomic Force Microscopy (AFM) was applied to monitor the morphology and roughness of the films. The properties and the morphology of the deposited films are compared in order to determine the effect of the particles formation on the material's quality.

SESSION FT2: INDUCTIVELY COUPLED PLASMAS I
Tuesday Afternoon, 11 October 2016
Room: 2a at 14:00
Steven Shannon, North Carolina State University, presiding

Contributed Papers

14:00

FT2 1 Control of ion energy distributions in inductively coupled ratio-frequency plasmas with a biased electrode* CHAN XUE, WEI LIU, FEI GAO, YOU-NIAN WANG, *School of Physics and Optoelectronic Technology, Dalian University of Technology, China* We measured the ion energy distribution (IED) and plasma density as a function of the voltage phase shift φ between the source and bias electrode in inductively coupled argon plasma driven at 13.56 MHz by using a retarding field energy analyzer and a commercial Langmuir probe, respectively. Our results demonstrate that under some certain discharge conditions, as the phase shift φ increases from 0 to 2π, the plasma potential slightly decreases with φ, while the IED exhibits drastic changes in both the IED width and the energy of bimodal distribution. To be specific, as φ increases from 0 to π, the IED width increases and the bimodal distribution shifts to high energy region. However the IED width almost keeps constant and the bimodal distribution shifts to low energy region, when φ increases from π to 2π.

*This work was supported by the National Natural Science Foundation of China (NSFC) (Grand Nos. 11335004, 11205025, 11405019).

14:15

FT2 2 Gas composition influence on ion energy distribution functions in an industrial ICP reactor with biased cathode DAVID PETERSON, STEVEN SHANNON, *North Carolina State Univ* DAVID COUMOU, SCOTT WHITE, *MKS Instruments RF Power Division* An industrial ICP reactor consisting of a top planar coil and RF biased lower electrode has been characterized using a hairpin resonator probe and gridded ion energy analyzer to measure electron density in the bulk plasma and ion energy distribution function (IEDF) at the surface of the biased cathode. Argon and oxygen were run at constant total flow with 20mTorr downstream pressure control with varying flow ratios between the two gases ranging from 0% to 100% oxygen content. ICP and bias power were adjusted to maintain constant electron density and sheath bias over this mixing matrix at four different setpoints reflecting high density / high bias, high density / low bias, low density / high bias, and low density / low bias. Although the fundamental parameters governing RF sheath behavior were held constant, several trends in ion energy distribution are observed with respect to gas composition (aside from the obvious influence of ion mass) that show considerable variation in measured IEDF particularly that can be attributed to ion collisions in the sheath as well as gas heating variation due to gas composition.

14:30

FT2 3 Studies on the radical species in inductively coupled Ar/CH_4 plasma using improved single Langmuir probe diagnostic methods and fluid simulation JU-HONG CHA, KWON-SANG SEO, JUNG YEOL LEE, HAE JUNE LEE, HO-JUN LEE, *Department of Electrical Engineering,Pusan National University, Busan, South Korea* An inductively coupled plasma source driven by 13.56MHz was prepared for the deposition of a-C:H thin film. Properties of the plasma source are investigated by fluid simulation including Navier-Stokes equation and home-made tuned single Langmuir probe. Signal attenuation ratios of the Langmuir probe at first and second harmonic frequency were 49dB and 46dB respectively. Numerical methods including fitting, digital smoothing, digital filter with window function were used to calculate the electron energy distribution accurately. Dependencies of plasma parameters on process were well agreed with simulation results. It was found that RF power, inlet pressure and composition ratio significantly affect to the electron density, temperature and energy distribution. Electron density and plasma potential profile were changed along the input power and gas pressure. Below the input power density of $0.1\mathrm{W/cm}^3$, higher plasma potential was observed at higher pressure. However, over the $0.1\mathrm{W/cm}^3$, lower plasma potential was observed along the higher pressure. This result was occurred owing to the change of electron energy distribution. And from the simulation results, the specific chemical reaction channel, not CxHy but CHx, affect to the radical density profile.

14:45

FT2 4 An electromagnetic approach to a small-scale microwave ICP-plasmajet MICHAEL KLUTE, *Theoretical Electrical Engineering, Ruhr University Bochum, Germany* HORIA-EUGEN PORTEANU, WOLFGANG HEINRICH, *Microwave Department, Ferdinand-Braun-Institut, Germany* PETER AWAKOWICZ, *Electrical Engineering and Plasma Technology, Ruhr University Bochum, Germany* RALF-PETER BRINKMANN, *Theoretical Electrical Engineering, Ruhr University Bochum, Germany* Microwave-driven plasmas-jets offer attractive properties for various technical applications. They are usually operated in a capacitive mode, known as E-Mode. Experimental experience however show a number of disadvantages for capacitive coupling such as high boundary sheath voltage and thus high electrical losses. Therefore in large scale plasmas inductive coupling, known as H-mode, is attractive. Recently Porteanu *et al.* [1] proposed a small scale plasma-jet operated as an inductive discharge. The key characteristic of the proposed plasma-jet is the implementation of an LC-resonance-circuit into a cavity resonator. In this work the proposed plasma-jet is examined theoretically. A global model for the electromagnetic fields and energy balance is presented. Consequent mathematical analysis of the electromagnetic fields leads to a description based on a sum of different modes. It is found that the modes of zero and first order can be identified with inductive and capacitive coupling. In a second step the matching network and its frequency depended characteristic are taken into account. Finally an investigation of stable working points and possible hysteresis effects is done.

[1]H. E. Porteanu *et al.*, Plasma Sources Sci. Technol. **22**, 035016 (2013).

15:00

FT2 5 Control of electron energy distribution by the power balance of the combined inductively and capacitively coupled RF plasmas JIN SEOK KIM, HO-JUN LEE, HAE JUNE LEE, *Pusan National University* The control of electron energy probability function (EEPF) is important to control discharge characteristics in materials processing. For example, O radical density increases by changing the EEPF in O_2 plasma, which provides high etching efficiency [1]. The effect of the power balance between the capacitively coupled plasma (CCP) and the inductively coupled plasma (ICP) on the EEPF in Ar and O_2 plasmas is investigated with a 1d3v (one-dimensional space and three-dimensional velocity domain) particle-in-cell (PIC) simulation for the combined inductively and capacitively coupled plasmas. The combined effects of the transverse electromagnetic and the longitudinal electrostatic fields are solved in PIC simulation at the same time. In a pressure range of a few mTorr, high energy electrons (>5 eV) are heated by the capacitive power in the sheath while low energy electrons (<5 eV) are heated by the inductive power in the bulk region. The EEPF has bi-Maxwellian distribution when the CCP power is dominant, but it changes to Maxwellian-like distribution with increasing inductive power. Finally, the EEPF changes to Druyvesteyn-like distribution when the inductive power is dominant.

[1]H. C. Lee and C. W. Chung, Plasma Sources Sci. Technol. **24**, 024001 (2015).

15:15

FT2 6 Neutral and ion dynamics at the plasma-surface interface region in inductively coupled plasmas* MARTIN BLAKE, *York Plasma Institute, University of York, Heslington, York, YO10 5DD* ANDREW ROBERT GIBSON, *2LPP, Ecole Polytechnique-CNRS-Uni Paris-Sud-UPMC, 91128 Palaiseau, France* KARI NIEMI, DEBORAH O'CONNELL, TIMO GANS, *York Plasma Institute, University of York, Heslington, York, YO10 5DD* Understanding the dynamics of the plasma-surface interface in low temperature, low pressure plasmas is critical for developing industrial processes. In this context atomic neutral species and ions both play an important role. Presented in this work is an experimental characterization of the plasma-surface interface region in plasmas produced in O_2/Ar and H_2/He, operated in capacitive and inductive modes in a gaseous electronics conference (GEC) reference cell. The industrially relevant pressure range of 1-10 Pa is investigated at varying powers and gas mixtures. The dissociation degree and mean electron energy are determined through comparing ratios of calculated excitation rates with those measured using phase resolved optical emission spectroscopy. Two excited states each for hydrogen and oxygen are compared with the rare gas admixture (either He or Ar) using the newly developed Energy Resolved Actinometry (ERA) technique. For the excitation dynamics both direct and dissociative electron impact excitation are accounted for. In addition, the ion energy distribution function at the surface has been measured using a retarding field energy analyzer.

*EPSRC manufacturing grant EP/K018388/1.

SESSION FT3: MICROPLASMAS

Tuesday Afternoon, 11 October 2016; Room: 2b at 14:00; D.Z. Pai, CNRS Universite de Poitiers, presiding

Invited Papers

14:00

FT3 1 Operating principles of microplasmas assisted by field emitting cathodes
AYYASWAMY VENKATTRAMAN, *University of California Merced*

Microplasmas have contributed to an exciting new direction in low-temperature plasma science and engineering with various applications including electronics, nanomaterial synthesis, and lighting to name a few. The rapid miniaturization of microplasma devices has provided the opportunity to exploit physical mechanisms that are considered unimportant in traditional macroscale plasmas. Specifically, the intense electric fields encountered in microplasma devices lead to an auxiliary source of electrons via field-induced electron emission from the electrodes. Also, recent advances in nano/microfabrication have resulted in the engineering of thin film materials (such as ultrananocrystalline diamond) with field emission threshold electric fields as low as 1 V/μm thereby allowing us to exploit them in microplasmas with dimensions $\sim$ 100 μm. In this regard, this talk deals with the principles that govern the operation of microplasma devices assisted by field emitting cathodes. Specifically, the talk will focus on the interesting interplay between field emission and the corresponding microplasma properties with surface-normal electric field serving as the link. Results are presented for the operating modes of field emission assisted microplasmas in the direct current and radio frequency/microwave regimes. The one-dimensional analyses include a combination of simplified global/spatial sheath models, fluid simulations as well as kinetic simulations using the particle-in-cell with Monte Carlo collisions (PIC-MCC) method. Two-dimensional fluid simulations are also presented for microcavity plasmas augmented by field emitting cathodes. The simulations are validated with experimental data whenever possible and a need for additional suitable experimental datasets is highlighted.

Contributed Papers

14:30

FT3 2 Low temperature, high-density microplasma plume generated in a micro-tube with variable inner diameter JIANMIN GOU, XINPEI LU, *Huazhong University of Science & Technology* A low temperature helium microplasma plume generated in a micro quartz tube with inner diameter decreasing from 245 μm to 6 μm is reported. The microplasma plume has a length of around 1.5 cm and reaches the position with its diameter down to 10 μm. Though the inner diameter of the tube is in sub-millimeter, the cross section of the tube is not fully filled with the plasma only until the tube inner diameter is down to 30 μm. The electron density estimated from H_α stark broadening increases as the inner diameter of the tube decreases. The ignition voltage increases from 11 kV to 40 kV as the diameter of the inner quartz tube decreases from 245 μm to 10 μm. Further analysis shows that, in order to ignite a non-equilibrium plasma plume in 1 μm diameter tube, the applied voltage of about 65 kV is needed and the plasma density could reach as high as on the order of 10^{18} cm^{-3}, which is interesting for the studies of several fundamental phenomena such as plasma sheath structure.

14:45

FT3 3 Enhanced lifetime for thin-dielectric microdischarge-arrays operating in DC REMI DUSSART, VALENTIN FELIX, *GREMI - Univ Orleans - CNRS* LAWRENCE OVERZET, *University of Texas at Dallas* OLIVIER AUBRY, ARNAUD STOLZ, PHILIPPE LEFAUCHEUX, *GREMI - Univ Orleans - CNRS* GREMI - UNIV ORLEANS - CNRS COLLABORATION, UNIVERSITY OF TEXAS AT DALLAS COLLABORATION Micro-hollow cathode discharge arrays using silicon as the cathode have a very limited lifetime because the silicon bubbles and initiates micro-arcing [1]. To avoid this destructive behavior, the same configuration was kept but, another material was selected for the cathode. Using micro and nanotechnologies ordinarily used in microelectronic and MEMS device fabrication, we made arrays of cathode boundary layer (CBL)-type microreactors consisting of nickel electrodes separated by a 6 μm thick SiO_2 layer. Microdischarges were ignited in arrays of ~100 μm diameter holes at different pressures (200750 Torr) in different gases. Electrical and optical measurements were made to characterize the arrays. Unlike the microdischarges produced using silicon cathodes, the Ni cathode discharges remain very stable with essentially no micro-arcing. DC currents between 50 and 900 μA flowed through each microreactor with a discharge voltage of typically 200 V. Stable V-I characteristics showing both the normal and abnormal regimes were observed and are consistent with the spread of the plasma over the cathode area. Due to their stability and lifetime, new applications of these DC, CBL-type microreactors can now be envisaged.

[1] V. Felix *et al.*, Plasma Sources Sci. Technol. **25**, 025021 (2016).

15:00

FT3 4 Global model of a micro hollow cathode discharge in Ar/N_2 used for nitride synthesis CLAUDIA LAZZARONI, SALIMA KASRI, *LSPM CNRS, Institut Galilee, Universite Sorbonne Paris Cite, Universite Paris 13* A global model of a Micro Hollow Cathode Discharge (MHCD) in argon (Ar) with an admixture of nitrogen (N_2), working at several hundreds of Torr, is presented. MHCDs allow high electron densities and therefore high dissociation degree of nitrogen to be reached which is particularly suited for nitride deposition given the high bond energy of molecular nitrogen. 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 particular focus is given to the atomic nitrogen density, a key parameter for the deposition and growth of nitride films. A parametric study is done varying the gas pressure and the N_2 fraction in Ar. Despite being fed by a DC power supply, MHCDs operate in steady state and in self-pulsed mode, both captured by the model. The effect of the MHCD mode (steady or self-pulsed) on the plasma parameters is also presented.

SESSION FT4: PLASMA DEPOSITION I
Tuesday Afternoon, 11 October 2016
Room: 3 at 14:00
Hirotaka Toyoda, Nagoya University Japan, presiding

Contributed Papers

14:00

FT4 1 Electrical and Structural Properties of Copper Thin Films Deposited by Novel RF Magnetized Plasma Sputtering with Gyratory Square-Shaped Arrangement by Bar Permanent Magnets MD AMZAD HOSSAIN, YASUNORI OHTSU, *Graduate School of Science and Engineering, Saga University, Japan* Rotating square-shaped arrangement by bar permanent magnets has been proposed for uniform target utilization in high-density radio frequency (RF) magnetized sputtering plasma. In this work, copper thin films are grown on unheated Si wafer by RF sputtering technique. The experiments are done in stainless-steel cylindrical vacuum chamber with outer diameter of 235 mm, inner diameter of 160 mm and 195 mm in height, whereas argon (Ar) gas pressure of 1.03 [Pa], rotating the iron yoke with speed of 40 [rpm,] sputtering time of 1.5 [h], and RF input power of 100 [W] at 13.56 [MHz] are realized. The deposited copper film thickness, electrical, structural properties and plasma density are investigated for case (a) without iron cover and case (b) with iron cover, respectively placed on the contact zone between the N-pole and the S-pole magnets. Radial profiles of the deposited copper thin film thickness and resistivity for case (b) are more uniform than case (a). It is found that the resistivities of deposited copper thin film for case (a) and (b) are approximately 7.89×10^{-8} Ω-m and 4.33×10^{-8} Ω-m, respectively at $r = 30$ mm. From AFM analysis, the uniformity of thin films grown throughout surface is better case (b) than case (a). The roughness of radial profile of the film thickness for case (a) and case (b) are 22.3% and 6.55%, respectively.

14:15

FT4 2 Lateral epitaxial overgrowth of silicon thick films during nanocluster assisted mesoplasma CVD MAKOTO KAMBARA, TESURO KOYANO, YUSUKE IMAMURA, TOYONOBU YOSHIDA, *The University of Tokyo* THE UNIVERSITY OF TOKYO TEAM Mesoplasma epitaxy has been applied to the deposition on a SiO_2 masked Si wafer to identify the feasibility of lift-off and layer transfer of the thick epitaxial films. Under a certain deposition condition, the Si epitaxial film was deposited over the patterned mask with 4 μm width. The surface topography on patterned mask has revealed that the epitaxial film grows laterally over the pattern from the Si window and its lateral epitaxial overgrowth (LEO) rate is 4-5 times faster than the vertical growth rate and reaches 2500 nm/sec at the trichlorosilane flow rate of 100 sccm. Growth model was developed, assuming the surface diffusion of the nanoclusters-constituent Si atoms on the mask surface and and also that the Cl etching effect of both SiO_2 and Si. The model reproduces reasonably the LEO tendency and identified the shorter diffusion length of 127 nm than that of the conventional CVD, as the unique LEO mode with cluster assisted epitaxy. Furthermore, as predicted by the model, the deposition at greater TCS rates successfully produces LEO on the pattern with wider 8 μm mask width as a result of LEO coverage before completion of the mask etching.

14:30

FT4 3 Dynamics of the formation and loss of boron atoms in a H_2/B_2H_6 microwave plasma C. Y. DULUARD, X. AUBERT, *LSPM, CNRS, Université Paris 13, 99 av J.-B. Clément, 93430 Villetaneuse, France* N. SADEGHI, *LIPhy (UMR5588) & LTM (UMR5129), Université de Grenoble & CNRS, Grenoble, France* A. GICQUEL, *LSPM, CNRS, Université Paris 13, 99 av J.-B. Clément, 93430 Villetaneuse, France* For further improvements in doped-diamond deposition technology, an understanding of the complex chemistry in $H_2/CH_4/B_2H_6$ plasmas is of general importance. In this context, a H_2/B_2H_6 plasma ignited by microwave power in a near resonant cavity at high pressure (100-200 mbar) is studied to measure the B-atom density in the ground state. The discharge is ignited in the gas mixture (0-135 ppm B_2H_6 in H_2) by a 2.45 GHz microwave generator, leading to the formation of a hemispheric plasma core, surrounded by a faint discharge halo filling the remaining reactor volume. Measurements with both laser induced fluorescence and resonant absoption with a boron hollow cathode lamp indicate that the B-atom density is higher in the halo than in the plasma core. When the absorption line-of-sight is positioned in the halo, the absorption is so strong that the upper detection limit is reached. To understand the mechanisms of creation and loss of boron atoms, time-resolved absorption measurements have been carried out in a pulsed plasma regime (10 Hz, duty cycle 50%). The study focuses on the influence of the total pressure, the partial pressure of B_2H_6, as well as the source power, on the growth and decay rates of boron atoms when the plasma is turned off.

14:45

FT4 4 Coatings deposition from liquid HMDSO films via conversion in dielectric barrier discharges SEBASTIAN DAHLE, WOLFGANG MAUS-FRIEDRICHS, *Clausthal University of Technology* The application of plasma discharges for the deposition of coatings is well established in the academic as well as the industrial sector. This is especially true for plasma-enhanced chemical vapour deposition of HMDSO. However, employing thick liquid films is an approach barely recognized, so far. We demonstrate the possibility of introducing thick liquid monomer films into plasma discharges in order to form solid coatings. The underlying processes are discussed including gas kinetics, reactions in the gas and liquid phases as well as at the gas-liquid interface. Finally, conclusions are drawn regarding the plasma-based deposition of highly complex coatings in-between plasma-chemistry and classic polymer chemistry via plasma-enhanced chemical solution deposition.

15:00

FT4 5 Atmospheric Pressure Low Temperature Plasma System for Additive Manufacturing MATTHEW BURNETTE, DAVID STAACK, *Texas A&M University* There is growing interest in using plasmas for additive manufacturing, however these methods use high temperature plasmas to melt the material. We have developed a novel technique of additive manufacturing using a low temperature dielectric barrier discharge (DBD) jet. The jet is attached to the head of a 3D printer to allow for precise control of the plasma's location. Various methods are employed to deposit the material, including using a vaporized precursor or depositing a liquid precursor directly onto the substrate or into the plasma via a nebulizer. Various materials can be deposited including metals (copper using copper (II) acetylacetonate), polymers (PMMA using the liquid monomer), and various hydrocarbon compounds (using alcohols or a 100% methane DBD jet). The rastering pattern for the 3D printer was modified for plasma deposition, since it was originally designed for thermoplastic extrusion. The design constraints for fill pattern selection for the plasma printer are influenced by substrate heating, deposition area, and precursor consumption. Depositions onto pressure and/or temperature sensitive substrates can be easily achieved. Deposition rates range up to 0.08 cm^3/hr using tris(2-methoxyethoxy)(vinyl)silane, however optimization can still be done on the system to improve the deposition rate. For example higher concentration of precursor can be combined with faster motion and higher discharge powers to increase the deposition rate without overheating the substrate.

15:15

FT4 6 Opportunities offered by the interaction of plasma and droplets to elaborate nanostructured oxide materials* MEHRDAD NIKRAVECH, ABDELKADER RAHMANI, *LSPM-Cnrs, Université Sorbonne Paris cité Paris13* The association of plasma and spray will permit to process materials where organometallic precursors are not available or economically non-reliable. The injection of aerosols in low pressure plasma results in the rapid evaporation of solvent and the rapid transformation of small amounts of precursors contained in each droplet leading to form nanoscale oxide particles. We developed two configurations of this technique: one is Spray Plasma that permits to deposit this layers on flat substrates; the second one is Fluidized Spray Plasma that permits to deposit thin layers on the surface of solid beads. The aim of this presentation is to describe the principles of this new technique together with several applications. The influence of experimental parameters to deposit various mixed metal oxides will be demonstrated: thin dense layers of nanostructured ZnO for photovoltaic applications, porous layers of $La_xSr_{1-x}MnO_3$ as the cathode for fuel cells, ZnO-Cu, NiO layers on solid pellets in fluidized bed for catalysis applications.

*Aknowledgement to Programme interdisciplinaire SPC Énergies de Demain.

SESSION GT1: PLASMA PROPULSION AND AEROSPACE APPLICATIONS I

Tuesday Afternoon, 11 October 2016; Room: 1 at 16:00; Trevor Lafleur, Ecole Polytechnique, presiding

Invited Papers

16:00

GT1 1 From laboratory plasma experiments to space plasma experiments with 'CubeSat' nano-satellites

CHRISTINE CHARLES, *Space Plasma and Plasma Propulsion Laboratory (SP3), RSPE, The Australian National University, Canberra, ACT260*

'CubeSat' nano-satellites provide low-cost access to space. SP3 laboratory's involvement in the European Union 'QB50' 'CubeSat' project [www.qb50.eu] which will launch into space 50 'CubeSats' from 27 Countries to study the ionosphere and the lower thermosphere will be presented. The Chi Kung laboratory plasma experiment and the Helicon Double Layer Thruster prototype can be tailored to investigate expanding magnetized plasma physics relevant to space physics (solar corona, Earth's aurora, adiabatic expansion and polytropic studies). Chi Kung is also used as a plasma wind tunnel for ground-based calibration of the University College London QB50 Ion Neutral Mass Spectrometer. Space qualification of the three Australian QB50 'CubeSats' (June 2016) is carried out in the WOMBAT XL space simulation chamber. The QB50 satellites have attitude control but altitude control is not a requirement. SP3 is developing end-to-end miniaturised radiofrequency plasma propulsion systems (such as the Pocket Rocket and the MiniHel thrusters with power and propellant sub-systems) for future 'CubeSat' missions.

Contributed Papers

16:30

GT1 2 Modeling plasma glow discharges in Air near a Mach 3 bow shock with KRONOS SEBASTIEN RASSOU, JULIEN LABAUNE, DENIS PACKAN, PAUL-QUENTIN ELIAS, *ONERA* In this work, plasma glow discharge in Air is modeled near a Mach 3 bow shock. Numerical simulations are performed using the coupling KRONOS which have been developed at ONERA. The flow field is modeled using the code CFD: CEDRE from ONERA and the electrical and plasma part by the EDF open-source code CODE_SATURNE. The plasma kinetic modeling consists on a two-term Boltzmann equation solver and a chemical reaction solver depending of the electric field. The coupling KRONOS is fully parallelized and run on ONERA supercomputers. The shock wave is formed by the propagation of a supersonic flow ($M = 3$) through a truncated conical model mounted with a central spike. Depending on the spike's voltage value, corona, glow or arc regime could be obtained in a steady flow. The parameters for the supersonic flow and the spike configurations are chosen to be in glow discharge regime and to reproduce the experimental setup. In our simulations, 12 species and 80 reactions (ionization, electronic or vibrational excitation, attachment etc ...) are considered to properly model the glow discharge and the afterglow. In a stationary flow, glow discharge is observed only at the upstream of the shock wave near the high voltage spike. Behind the bow shock, in the afterglow, negative ions are provided by electrons attachment with O2. The negative ions flow convection ensures the electrical conduction and the establishment of the glow discharge.

16:45

GT1 3 MHD thrust vectoring of a rocket engine JULIEN LABAUNE, DENIS PACKAN, FABIEN THOLIN, LAURENT CHEMARTIN, *ONERA* THIERRY STILLACE, FREDERIC MASSON, *CNES Launcher Directorate* In this work, the possibility to use MagnetoHydroDynamics (MHD) to vectorize the thrust of a solid propellant rocket engine exhaust is investigated. Using a magnetic field for vectoring offers a mass gain and a reusability advantage compared to standard gimbaled, elastomer-joint systems. Analytical and numerical models were used to evaluate the flow deviation with a 1 Tesla magnetic field inside the nozzle. The fluid flow in the resistive MHD approximation is calculated using the KRONOS code from ONERA, coupling the hypersonic CFD platform CEDRE and the electrical code SATURNE from EDF. A critical parameter of these simulations is the electrical conductivity, which was evaluated using a set of equilibrium calculations with 25 species. Two models were used: local thermodynamic equilibrium and frozen flow. In both cases, chlorine captures a large fraction of free electrons, limiting the electrical conductivity to a value inadequate for thrust vectoring applications. However, when using chlorine-free propergols with 1% in mass of alkali, an MHD thrust vectoring of several degrees was obtained.

17:00

GT1 4 2D Particle-In-Cell simulations of the electron-cyclotron instability and associated anomalous transport in Hall-Effect Thrusters* VIVIEN CROES, TREVOR LAFLEUR, *Ecole Polytechnique* ZDENEK BONAVENTURA, *Masarykova Univerzita* FRANÇOIS PÉCHEREAU, *CERFACS* ANNE BOURDON, PASCAL CHABERT, *Ecole Polytechnique* This work studies the electron-cyclotron instability in Hall-Effect Thrusters (HETs) using a 2D Particle-In-Cell (PIC) simulation. The simulation is configured with a Cartesian coordinate system where a magnetic field, B_0, is aligned along the X-axis (radial direction, including absorbing walls), a constant electric field, E_0, along the Z-axis (axial direction, perpendicular to simulation plane), and the $E_0 x B_0$ direction along the Y-axis (O direction, with periodic boundaries). Although for low plasma densities classical electron-neutral collisions theory describes well electron transport, at sufficiently high densities (as measured in HETs) a strong instability can be observed that enhances the electron mobility, even in the absence of collisions. The instability generates high frequency (~MHz) and short wavelength (~mm) fluctuations in both the electric field and charged particle densities. We investigate the correlation between these fluctuations and their role with anomalous electron transport; complementing previous 1D simulations. Plasma is self-consistently heated by the instability, but since the latter does not reach saturation in an infinitely long 2D system, saturation is achieved through implementation of a finite axial length that models convection in E_0 direction.

*With support of Safran Aircraft Engines.

17:15

GT1 5 Effects of Electrode Oxidation on the RailPAc Plasma Actuator Gliding Arc MILES GRAY, YOUNG-JOON CHOI, JAYANT SIROHI, LAXMINARAYAN L RAJA, *University of Texas at Austin* The rail plasma actuator (RailPAc) has been proposed as a high momentum atmospheric-pressure aerodynamic flow control technique using the principle of MHD forcing. We have previously studied the physics of the RailPAc device and characterized arc structure and dynamics during operation. We have recently shown that the arc dynamic behavior is strongly influenced by the state of the electrode surface and the arc root mode of attachment to that surface. These plasma surface interaction effects have significant implications for the design of practical gliding arc actuators. In this talk we report on the structure of anode and cathode root attachment as a function of the electrode surface state and their impact on overall motion of arc column and the aerodynamic forcing performance. We find that in particular, anode root attachment is the limiting process that limits the overall motion of the arc column, and hence the device performance. We also find that the oxidation state of the anode surface has strongest influence on the anode root motion and hence can be used to alleviate arc root attachment related limitations on the RailPAc performance.

SESSION GT2: CAPACITIVELY COUPLED PLASMAS I
Tuesday Afternoon, 11 October 2016
Room: 2a at 16:00
Aranko Derzsi, Hungarian Academy of Sciences, presiding

Contributed Papers

16:00
GT2 1 Influence of the normal modes on the plasma uniformity in large scale CCP reactors* DENIS EREMIN, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Ruhr University Bochum* BARTON LANE, MASAAKI MATSUKUMA, PETER VENTZEK, *Tokyo Electron Ltd.* Large scale capacitively coupled plasmas (CCP) driven by sources with high frequency components often exhibit phenomena which are absent in relatively well understood small scale CCPs driven at low frequencies. Of particular interest are such phenomena which affect discharge parameters of direct relevance to the plasma processing applications. One of such parameters is plasma uniformity. By using a self-consistent 2d3v Particle-in-cell/Monte-Carlo (PIC/MCC) code parallelized on GPU we have been able to show that uniformity of the plasma generated is influenced predominantly by two factors, the ionization pattern caused by high-energy electrons and the average temperature of low-energy plasma electrons. The heating mechanisms for these two groups of electrons appear to be different leading to different transversal (radial) profiles of the corresponding factors, which is well captured by the kinetic PIC/MCC code. We find that the heating mechanisms are intrinsically connected with excitation of normal modes inherent to a plasma-filled CCP reactor. In this work we study the wave nature of these phenomena, such as their excitation, propagation, and interaction with electrons.

*Supported by SFB-TR 87 project of the German Research Foundation and by the "Experimental and numerical analysis of very high frequency capacitively coupled plasma discharges" mutual research project between RUB and Tokyo Electron Ltd.

16:15
GT2 2 Striations in electronegative capacitively coupled radio frequency plasmas JULIAN SCHULZE, *Institute for Electrical Engineering, Ruhr-University Bochum, Germany* YONG-XIN LIU, *School of Physics, Dalian University of Technology, China* EDMUND SCHUENGEL, *Department of Physics, West Virginia University, USA* IHOR KOROLOV, *Hungarian Academy of Sciences* YOU-NIAN WANG, *School of Physics, Dalian University of Technology, China* ZOLTAN DONKO, *Hungarian Academy of Sciences* Self-organized spatial structures in the light emission from the ion-ion capacitive radio frequency plasma of an electronegative gas (CF_4) are observed experimentally by Phase Resolved Optical Emission Spectroscopy for the first time. Their formation is analyzed and understood based on particle-based kinetic simulations. These "striations" are found to be generated by a resonance between the external driving radio-frequency and the eigenfrequency of the ion-ion plasma that leads to a modulation of the electric field, the ion densities, as well as the energy gain and loss processes of electrons in the plasma. The growth of the instability is followed by the numerical simulations [1]. The presentation introduces this effect conceptually and explains its physical origin.

[1] Y.-X. Liu *et al.* 2016 Phys. Rev. Lett. accepted for publication.

16:30
GT2 3 Parametric investigations of striations in electronegative capacitively coupled radio-frequency plasmas* YONG-XIN LIU, *School of Physics and Optoelectronic Technology, Dalian University of Technology, China* EDMUND SCHÜNGEL, *Department of Physics, West Virginia University, Morgantown, USA* IHOR KOROLOV, ZOLTAN DONKO, *Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary* JULIAN SCHULZE, *Department of Physics, West Virginia University, Morgantown, USA and Institute for Electrical Engineering, Ruhr-University Bochum, Germany* YOU-NIAN WANG, *School of Physics and Optoelectronic Technology, Dalian University of Technology, China* Striated structures in light emission have been observed by Phase Resolved Optical Emission Spectroscopy (PROES) and analyzed based on particle-based kinetic simulations in capacitively coupled rf CF4 plasmas. On this basis, we conduct a systematic study on the effects of external parameters on the striated structure by PROES and particle-based kinetic simulations. Our results exhibit that at 100 Pa pressure and 300 V voltage amplitude striations generally occur within a certain driving frequency range, i.e., between 2 MHz and 18 MHz, and the distance between the ion density maxima decreases with rising driving frequency. A mode discharge transition from the "drift-ambipolar" into "striation" mode could be observed by increasing the pressure or rf voltage. The reasons for these observations are further understood by the analytical solution of a simply model of the ion-ion plasma.

*This work has been supported by the National Natural Science Foundation of China (NSFC) (Grant Nos. 11335004 and 11405018).

16:45
GT2 4 Two Dimensional Particle-in-cell/Monte Carlo (PIC/MC) Simulation of Radio Frequency Capacitively Coupled Plasmas with a Dielectric Side Wall Boundary* YUE LIU, JEAN-PAUL BOOTH, PASCAL CHABERT, *LPP, CNRS, Ecole Polytechnique-UPMC-UPSud-UPSay* COLD PLASMA TEAM, LPP TEAM The majority of previous two dimensional (usually fluid) simulations of radio frequency capacitively coupled plasmas have focused on geometrically-asymmetric reactors (with a much larger grounded electrode than power electrode), which produces a strong dc self-bias. However, a commonly-used geometry comprises electrodes of equal area surrounded by a dielectric side wall, but this has not been widely simulated. We have developed a two dimensional (Cartesian) PIC/MC code based on the work of Hongyu Wang, Wei Jiang and Younian Wang, to simulate argon plasmas in this kind of chamber. Even using a thick dielectric, a peak in plasma density and electron power deposition is adjacent to the dielectric. The profiles of the electron and ion fluxes show that the period-averaged currents to the powered electrode are not locally balanced; the electron flux peaks closer to the dielectric edge, before dropping sharply. Finally, the effect of the dielectric thickness on the surface charge distribution and the angular distributions of ions arriving at boundaries is examined.

*This work is supported by China Scholarship Council.

17:00
GT2 5 Virtual IED sensor at an rf-biased electrode in low-pressure plasma* MARIA BOGDANOVA, *Faculty of Physics, Moscow State University, MSU, Moscow Russia* DMITRY LOPAEV, *Skobeltsyn Institute of Nuclear Physics, Moscow State University, SINP MSU, Moscow Russia* SERGEY ZYRYANOV, *Faculty of Physics, Moscow State University, MSU, Moscow Russia* ALEXANDER RAKHIMOV, *Skobeltsyn Institute of Nuclear*

Physics, Moscow State University, SINP MSU, Moscow Russia The majority of present-day technologies resort to ion-assisted processes in rf low-pressure plasma. In order to control the process precisely, the energy distribution of ions (IED) bombarding the sample placed on the rf-biased electrode should be tracked. In this work the "Virtual IED sensor" concept is considered. The idea is to obtain the IED "virtually" from the plasma sheath model including a set of externally measurable discharge parameters. The applicability of the "Virtual IED sensor" concept was studied for dual-frequency asymmetric ICP and CCP discharges. The IED measurements were carried out in Ar and H_2 plasmas in a wide range of conditions. The calculated IEDs were compared to those measured by the Retarded Field Energy Analyzer. To calibrate the "Virtual IED sensor", the ion flux was measured by the pulsed self-bias method and then compared to plasma density measurements by Langmuir and hairpin probes. It is shown that if there is a reliable calibration procedure, the "Virtual IED sensor" can be successfully realized on the basis of analytical and semianalytical plasma sheath models including measurable discharge parameters.

*This research is supported by Russian Science Foundation (RSF) Grant 14-12-01012.

17:15

GT2 6 Precise measurements of neutral gas temperature using Fiber Bragg Grating sensor in Argon capacitively coupled plasmas* DAOMAN HAN, ZIGENG LIU, YONGXIN LIU, WEI PENG, YOUNIAN WANG, *School of Physics and Optoelectronic Technology, Dalian University of Technology,* Neutral gas temperature was measured using Fiber Bragg Grating sensor (FBGs) in capacitively coupled argon plasmas. Thermometry is based on the thermal equilibrium between the sensor and neutral gases, which is found to become faster with increasing pressure. It is also observed that the neutral gas temperature is higher than the room temperature by 10~120 °depending on the experiental conditions, and gas temperature shows significant non-uniformity in space. In addition, radial profiles of neutral temperature at different pressures, resemble these of ion density, obtained by a floating double probe. Specifically, at low pressure, neutral gas temperature and ion density peak at the center of the reactor, while the peak appears at the edge of the electrode at higher pressure. The neutral gas heating is mainly caused by the elastic collisions of Ar+ with neutral gas atoms in the sheath region after Ar+ gaining a certain energy.

*This work was supported by the National Natural Science Foundation of China (NSFC) (Grants No. 11335004, 11405018, and 61137005).

SESSION GT3: DISCHARGES IN LIQUIDS I
Tuesday Afternoon, 11 October 2016; Room: 2b at 16:00;

Invited Papers

16:00

GT3 1 Plasma-water systems studied with optical diagnostics including sum-frequency generation spectroscopy
TSUYOHITO ITO, *Osaka University*

Recently, various applications of plasma-water systems have been reported, such as materials synthesis, agricultural applications, and medical treatments. As one of basic studies of such systems, we are investigating water surface structure influenced by a plasma via vibrational sum-frequency generation spectroscopy. Vibrational sum-frequency generation spectroscopy is known to be an interfacially active diagnostic technique, as such process occurs in noncentrosymmetric medium. Visible and wavenumber-tunable infrared beams are simultaneously irradiated to the interface. The interfacial water has ice-like (~3200 cm^{-1}), liquid-like (~3400 cm^{-1}), and free OH (3700 cm^{-1}) structures (assignment of the ice-like structure still remains contentious), and the intensity of the signal becomes stronger when the tunable infrared beam resonates with a vibration of the structures. The results indicate that with generating air dielectric barrier discharges for supplying reactive species to the water surface, all investigated signals originating from the above-mentioned three structures decrease. Furthermore, the signal strengths are recovered after terminating the plasma generation. We currently believe that the surface density of the reactive species should be high when they are found at the water surface. Details on the experimental results of the sum-frequency generation spectroscopy, as well as other spectroscopic results of plasma-water systems, will be presented at the conference.

Contributed Papers

16:30

GT3 2 Simulation of Discharge Production in a Water Vapour Layer on an Electrode MOHAMMAD KARIM, BENJAMIN EVANS, LEONIDAS ASIMAKOULAS, KENNETH STALDER, THOMAS FIELD, BILL GRAHAM, *Queen's University Belfast, N.Ireland* TOMOYUKI MURAKAMI, *Seikei University, Tokyo, Japan* Electrical discharges in water are receiving increasing attention because of chemical, environmental and biomedical applications.The work to be presented focuses on plasmas created directly in high conductivity water, saline solution. Here the plasma is produced at low voltage (~200V) and is clearly associated with an initial vapour layer on the electrode surface that isolates the electrode from the liquid. In a previous paper [1] a finite element multiphysics program, incorporating all relevant electrical and thermal properties of the solution was shown to reproduce the experimentally observed pre-plasma vapour layer behaviour. The results of a simulation of the plasma production in vapour layers of the same size and shape as predicted in [1] will be presented, At present inert gas fills the "vapour layer". However this produces spatial distributions of the electron parameters that are consistent with the electric fields predicted in the original simulations. The water plasma simulation recently developed by Murakami is currently being included. It is anticipated that results of the coupled codes, showing the temporal and 2-D spatial development of the vapour and plasma, will be presented.

[1]L. Schaper, W. G. Graham, and K. R. Stalder, Plasma Sources Sci. Technol. **20**, 034003 (2011).

16:45

GT3 3 Nanosecond time resolved spectral characteristics of a pulsed discharge in water EMILE CARBONE, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum, 44780 Germany* BANG-DOU HUANG, YI-KANG PU, *Department of Engineering Physics, Tsinghua University, Beijing 100084, People's Republic of China* UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum, 44780 Germany* The dynamics of short pulsed plasmas generated directly inside liquids are still not well understood. Such discharges are highly collisional making them difficult to investigate experimentally. In this contribution, we present the experimental characterization of a stable nanosecond pulsed discharge in water with a pin to plate configuration. The peak applied voltage is 25 kV with a pulse duration of about 15 ns and 25 Hz repetition frequency. Although the discharge is intrinsically stable (breakdown jitter less than 5 ns), an optical delay line was constructed to couple the light into a spectrometer (1200 g/mm, 30 cm focal length). The plasma light is then spectrally resolved with (sub)-nanosecond temporal resolution using a streak camera. This allows us to measure without jitter the spectral characteristics of the discharge with nanosecond temporal resolution. The plasma emission is studied and no atomic lines or molecular bands are observed. Instead, a large continuum emission spectrum over the complete visible range is measured both during the discharge and afterglow periods. The possible origins of this continuum are discussed.

17:00

GT3 4 Spectral analysis of optical emission of microplasma in sea water* VLADISLAV GAMALEEV, HAYATO MORITA, JUNSEOK OH, HIROSHI FURUTA, AKIMITSU HATTA, *Kochi University of Technology* This work presents an analysis of optical emission spectra from microplasma in three types of liquid, namely artificial sea water composed of 10 typical agents (10ASW), reference solutions each containing a single agent (NaCl, $MgCl_2+H_2O$, Na_2SO_4, $CaCl_2$, KCl, $NaHCO_3$, KBr, $NaHCO_3$, H_3BO_3, $SrCl_2+H_2O$, NaF) and naturally sampled deep sea water (DSW). Microplasma was operated using a needle(Pd)-to-plate(Pt) electrode system sunk into each liquid in a quartz cuvette. The radius of the tip of the needle was 50μm and the gap between the electrodes was set at 20μm. An inpulse generator circuit, consisting of a MOSFET switch, a capacitor, an inductor and the resistance of the liquid between the electrodes, was used as a pulse current source for operation of discharges. In the spectra, the emission peaks for the main components of sea water and contaminants from the electrodes were detected. Spectra for reference solutions were examined to enable the identification of unassigned peaks in the spectra for sea water. Analysis of the Stark broadening of Hα peak was carried out to estimate the electron density of the plasma under various conditions. The characteristics of microplasma discharge in sea water and the analysis of the optical emission spectra will be presented.

*This work was supported by JSPS KAKENHI Grant Number 26600129.

17:15

GT3 5 Numerical investigation of the interaction of positive streamers with bubbles floating on a liquid surface* NATALIA YU. BABAEVA, GEORGE V. NAIDIS, *Joint Institute for High Temperatures Russian Academy of Sciences* MARK J. KUSHNER, *University of Michigan* Streamer discharges in air intersecting with liquids are being investigated to produce reactivity in the liquid. In this talk, we discuss results from a 2-d computational investigation of streamers in air intersecting an isolated liquid, air filled bubble floating on a liquid surface. The 15 mm diameter bubble is conducting water ($\varepsilon/\varepsilon_0 = 80$, $\sigma = 7.5 \times 10^{-4}\Omega^{-1}$ cm^{-1}) or transformer oil ($\varepsilon/\varepsilon_0 = 2.2$, $\sigma = 1.5 \times 10^{-13}\Omega^{-1}$ cm^{-1}) [1]. A needle electrode is positioned d=0–10 mm from the bubble center. With a water bubble (d=0) the streamer slides along the external surface but does not penetrate the bubble due to electric field screening by the conducting shell. If the electrode is shifted (d=3-10 mm) the streamer deviates from the vertical and adheres to the bubble. If the electrode is inserted inside the bubble, the streamer path depends on how deep the electrode penetrates. For shallow penetration, the streamer propagates along the inner surface of the bubble. For deep penetration the streamer takes the shortest path down through the gas. Due to the low conductivity of the oil bubble shell the electric field penetrates into the interior of the bubble. The streamer can then be re-initiated inside the bubble. Charge accumulation on both sides of the bubble shell and perforation of the shell will be also discussed.

*NYB, GVN supported by Russian Sci. Found. (14-12-01295). MJK by US Natl. Sci. Found. and Dept. of Energy.

[1]Yu Akishev *et al.*, Plasma Sources Sci. Technol. **24**, 065021 (2015).

SESSION GT4: MAGNETRONS I
Tuesday Afternoon, 11 October 2016
Room: 3 at 16:00
Tomas Kozak, University of West Bhohemia, presiding

Contributed Papers

16:00

GT4 1 First measurements of the temporal evolution of the plasma density in HiPIMS discharges using THz time domain spectroscopy STEFFEN M. MEIER, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum, Germany* ANTE HECIMOVIC, *Institute for Application-Oriented Plasma Physics, Ruhr-University Bochum, Germany* TSANKO V. TSANKOV, DIRK LUGGENHÖLSCHER, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum, Germany* High Power Impulse Magnetron Sputtering (HiPIMS), commonly used for coating and deposition applications, are characterized by high power and plasma densities, short pulse lengths and a complex confining magnetic field. This poses great challenges for the diagnostics, both in terms of temporal resolution and in being non-perturbative. Therefore, up to now the plasma density in the confinement region of the magnetron during HiPIMS discharges was known only approximately from numerical simulations or estimations from optical measurements. Our recent development of the dual-frequency multichannel boxcar THz time domain spectroscopy now offers the possibility for a direct measurement of the plasma density in the confinement region of the magnetron. It allows the determination of line-integrated plasma densities above $1 \cdot 10^{12}$ cm^{-2} with a very high temporal resolution in the sub-ns-range. Here, the development of the technique is briefly outlined and its application to a 5 cm diameter HiPIMS discharge with a Ti target under various conditions is presented. Plasma density evolution with a temporal resolution of $\approx 4\mu s$ is shown. The results are correlated to temporally resolved optical emission measurements providing insight into the discharge processes.

16:15

GT4 2 An ionization region model of the reactive Ar/O_2 high power impulse magnetron sputtering discharge JON TOMAS GUDMUNDSSON, *University of Iceland, Reykjavik, Iceland* DANIEL LUNDIN, *LPGP, Universite Paris-Sud, Orsay, France* NILS BRENNING, MICHEL A. RAADU, CHUNQING HUO, *KTH-Royal Institute of Technology, SE-100 44, Stockholm, Sweden* TIBERIU MINEA, *LPGP, Universite Paris-Sud, Orsay, France* A reactive ionization region model (R-IRM) is developed to describe the reactive Ar/O_2 high power impulse magnetron sputtering (HiPIMS) discharge with titanium target. We compare the discharge properties when the discharge is operated in the two well established operating modes, the metal mode and the poisoned mode. Experimentally, it is found that in the metal mode the discharge current waveform displays a typical non-reactive evolution, while in the poisoned mode the discharge current waveform becomes distinctly triangular and the current increases significantly. Using the R-IRM we find that when the discharge is operated in the metal mode Ar^+ and Ti^+-ions contribute most significantly (roughly equal amounts) to the discharge current while in the poisoned mode the Ar^+-ions contribute most significantly to the discharge current while the contribution of O^+-ions and secondary electron emission is much smaller. Furthermore, we find that recycling of ionized atoms coming from the target are required for the current generation in both modes of operation. In the metal mode self-sputter recycling dominates and in the poisoned mode working gas recycling dominates, and it is concluded that the dominating type of recycling determines the discharge current waveform.

16:30

GT4 3 Standing helicon induced by a rapidly bent magnetic field in plasmas* KAZUNORI TAKAHASHI, SHO TAKAYAMA, ATSUSHI KOMURO, AKIRA ANDO, *Tohoku Univ* PLASMA PHYSICS TEAM An electron energy probability function and an rf magnetic field are measured in an rf hydrogen helicon source, where axial and transverse static magnetic fields are applied to the source by solenoids and to the diffusion chamber by filter magnets, respectively. It is demonstrated that the helicon wave is reflected by the rapidly bent magnetic field and the resultant standing wave heats the electrons between the source and the magnetic filter, while the electron cooling effect by the magnetic filter is maintained. It is interpreted that the standing wave is generated by the presence of spatially localized change of a refractive index. The application to the hydrogen negative ion source used for the neutral beam injection system for fusion plasma heating is discussed.

*This work is partially supported by grant-in-aid for scientific research (16H04084 and 26247096) from the Japan Society for the Promotion of Science.

16:45

GT4 4 Anomalous cross-B field transport and spokes in HiPIMS plasma ANTE HECIMOVIC, CHRISTIAN MASZL, VOLKER SCHULZ-VON DER GATHEN, ACHIM VON KEUDELL, *Ruhr University Bochum* The rotation of localised ionisation zones, i.e. spokes, in magnetron discharge is investigated as a function of discharge current, ranging from 10 mA (current density 0.5 mA cm^{-2}) to 140 A (7 A cm^{-2}). The presence of spokes throughout the complete discharge current range indicates that the spokes are an intrinsic property of a magnetron sputtering plasma discharge. Up to discharge currents of several amperes, the spokes rotate in a retrograde ExB direction and beyond the spokes rotate in a ExB direction. In this contribution we present experimental evidence that anomalous diffusion is triggered by the appearance of spokes rotating in the ExB direction. The Hall parameter $\omega_{ce}\tau_c$, product of the electron cyclotron frequency and the classical collision time, reduces from Bohm diffusion values (16 and higher) down to the value of 3 as spokes appear, indicating anomalous cross-B field transport. The ion diffusion coefficients calculated from a sideways image of the spoke is six times higher than Bohm diffusion coefficients, which is consistent with the reduction of the Hall parameter.

17:00

GT4 5 The self scattering regime of reactive high power impulse magnetron sputtering of chromium and nitrogen WOLFGANG BREILMANN, CHRISTIAN MASZL, ANTE HECIMOVIC, JAN BENEDIKT, ACHIM VON KEUDELL, *Ruhr-University Bochum* High power impulse magnetron sputtering (HiPIMS) is a technique for deposition of thin films. It is essential to understand the plasma dynamics in reactive HiPIMS to improve the process of thin film deposition. In this work we investigate the influence of nitrogen admixture to an argon-chromium HiPIMS discharge. Time resolved ion energy distribution functions (IEDF) were measured by means of time and energy resolved mass spectrometry with a temporal resolution of 2 μs. The measurements were performed for 150 μs long HiPIMS pulses with a repetition frequency of 20 Hz. A 2" target was used. The working gas mixture was varied from pure argon to pure nitrogen with a constant pressure of 0.5 Pa. Peak current densities of 1.5 A/cm^2 and 4 A/cm^2 were chosen. When operating at high current and pure nitrogen atmosphere the IEDFs of chromium show that only a small amount of ions reaches the mass spectrometer, while for the low current case this is not observed. It is postulated that self-scattering of chromion ions by chromium ions reduces the flux to the mass spectrometer. This is very pronounced in the case of pure nitrogen due to increased confinement of the discharge, and thus a higher density of charged particles in front of the target.

17:15

GT4 6 Scattering of magnetized electrons at the boundary of low temperature plasmas* DENNIS KRUEGER, JAN TRIESCHMANN, RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Germany* Magnetized low temperature plasmas with magnetic fields of some 10 to 100 mT are characterized by an electron Larmor radius small compared to all other length scales of the system. In this regime, the classical drift approximation applies. Inside the plasma boundary sheath, this approach breaks down, as the sheath scale is given by the Debye length, which is even smaller than the Larmor radius. When applying different models for these domains, an appropriate boundary condition for the interface has to be utilized. This work investigates the dynamics at this interface with the help of a 3D kinetic single electron model. A comprehensive comparison of two selected sheath models, a classical bohm sheath and the assumption of a hard wall is implemented. Thereby the influence of these models with respect to specific gyro coordinates is investigated and used to characterize the respective system dynamics. Moreover effects like the drift of the guiding center due to the large $\vec{E} \times \vec{B}$ drift inside the sheath, which leads to a cross field diffusion similar to collisions outside the sheath, is analyzed and compared.

*This work is supported by the German Research Foundation (DFG) in the frame of the transregional collaborative research centre TRR 87.

SESSION HT6: POSTER SESSION I
Tuesday Evening, 11 October 2016
Exhibit Foyer at 17:30

HT6 1 PLASMA SCIENCE

HT6 2 Numerical simulation of low-temperature helium plasma source for biomedical applications* VLADIMIR BEKASOV, ROMAN ZAMCHY, ANATOLY KUDRYAVTSEV, *St. Petersburg State University* Numerical simulation of low-temperature helium plasma for biomedical applications was conducted. The plasma source is presented as a rod electrode located above the grounded plate. Helium acts as a working gas, which is supplied to the discharge through a quartz tube surrounding the rod electrode. An AC voltage with a frequency of 13 kHz and amplitude of up to 3 kV is applied to the electrode. Distance between rod tip and plate varies from 1 to 8 centimeters. Helium blow rate is considered in the range from 1 to 10 m / s. For a description of the discharge, in this paper, two-dimensional extended fluid model was presented. It consists of the continuity equations for calculating the concentration of particles, the energy balance equation for finding the electron temperature and the Poisson equation for electric fields. To calculate the velocity of neutral particles Navier-Stokes equations was solved, and thermal conductivity equation was solved for calculating the heating of the neutral gas.

*The work was supported by Saint Petersburg State University (Grant ?11.37.212.2016).

HT6 3 Surface discharges generated at metal-semiconductor-gas triple junctions DAVID PAI, DAVID BABONNEAU, SOPHIE CAMELIO, *Institut PPRIME (CNRS UPR 3346, Université de Poitiers, ISAE-ENSMA)* SVEN STAUSS, KAZUO TERASHIMA, *University of Tokyo* Discharges in air at atmospheric pressure as well as high-pressure CO_2 up to 15 atm are generated on silicon surfaces using reactor geometries typical of surface dielectric barrier discharges (DBDs), in order to investigate plasma generation and properties at metal-semiconductor-gas triple junctions. Short (10 ns) or long (200 ns) high-voltage pulses are applied at pulse repetition frequencies of 1 – 1000 Hz. Both p- and n-type silicon are investigated at different doping levels. Discharge generation can be achieved at applied voltages of about 1 kV or less, despite using silicon layers of 0.5 – 1 mm thickness. The discharge current differs in character from that of other types of nanosecond discharges, such as glows, sparks, and DBDs. The experimental characterization of plasma and surface properties is also presented.

HT6 4 Generation of anomalously energetic suprathermal electrons by an electron beam interacting with a nonuniform plasma IGOR KAGANOVICH,* *Princeton Plasma Phys Lab* DMYTRO SYDORENKO, *University of Alberta, Edmonton, Alberta T6G 2E1, Canada* PETER L. G. VENTZEK, *Tokyo Electron America, Austin, Texas 78741, USA* Electrons emitted from electrodes are accelerated by the sheath electric field and become the electron beams penetrating the plasma. The electron beam can interact with the plasma in collisionless manner via two-stream instability and produce suprathermal electrons. In order to understand the mechanism of suprathermal electrons acceleration, a beam-plasma system was simulated using a 1D3V particle-in-cell code EDIPIC. These simulation results show that the acceleration may be caused by the effects related to the plasma nonuniformity. The electron beam excites plasma waves whose wavelength and phase speed gradually decrease towards anode. The short waves near the anode accelerate plasma bulk electrons to suprathermal energies. Rich complexity of beam-plasma interaction phenomena was also observed: intermittency and multiple regimes of two-stream instability in a dc discharge, band structure of the growth rate of the two-stream instability of an electron beam propagating in a bounded plasma, multi-stage acceleration of electrons in a finite system.

*This research was funded by US Department of Energy.

HT6 5 Influence of pressure on ion energy distribution functions in EUV-induced hydrogen plasmas T.H.M. VAN DE VEN, P. REEFMAN, *Eindhoven University of Technology* C.A. DE MEIJERE, *ASML* V.Y. BANINE, *Eindhoven University of Technology and ASML* J. BECKERS, *Eindhoven University of Technology* Next-generation lithography tools currently use Extreme Ultraviolet (EUV) radiation to create even smaller features on computer chips. The high energy photons (92 eV) induce a plasma in the low pressure background gas by photoionization. Industries have realized that these plasmas are of significant importance with respect to machine lifetime because impacting ions affect exposed surfaces. The mass resolved ion energy distribution function (IEDF) is therefore one of the main plasma parameters of interest. In this research an ion mass spectrometer is used to investigate IEDFs of ions impacting on surfaces in EUV-induced plasmas. EUV radiation is focused into a vessel with a low pressure hydrogen environment. Here, photoionization creates free electrons with energies up to 76 eV, which further ionize the background gas. The influence of the pressure on plasma composition and IEDFs has been investigated in the range 0.1-10 Pa. In general the ion fluxes towards the surface increase with pressure. However, above 5 Pa the flux of H_2^+ is not affected by the increase in pressure due to the balance between the creation of H_2^+ and the conversion of H_2^+ to H_3^+. These results will be used to benchmark plasma scaling models and verify numerical simulations.

HT6 6 PLASMA BOUNDARIES: SHEATHS, BOUNDARY LAYERS, OTHERS

HT6 7 Plasma forces on deposited particles LUCAS HEIJMANS, SANDER NIJDAM, *Eindhoven University of Technology* A plasma can have many effects on a substrate. In this contribution we focus on its effects on micrometer sized particles on the substrate. We are especially interested in forces acting on these particles. These have been suggested to be responsible for the lunar glow observed by the Apollo mission astronauts. They have recently also attracted interest as a possible cleaning mechanism for the high-tech industry. We will present experimental measurements of the forces acting on a particle on a substrate under influence of a plasma. To this extend we have developed two specialised experimental setups. They use extreme accelerations (up to one million times the earth gravitational acceleration) to balance forces on the particle. We will show quantitative measurements of the plasma force effects, and show what underlying physical effects cause them.

HT6 8 Hydrodynamic ion sound instability in systems of a finite length O. KOSHKAROV, O. CHAPURIN, A. SMOLYAKOV, *University of Saskatchewan, Saskatoon SK, Canada* I. KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton NJ, USA* V. ILGISONIS, *National Research Centre Kurchatov Institute, Moscow,*

TUESDAY EVENING \ HT6

Russia Plasmas permeated by an energetic ion beam is prone to the kinetic ion-sound instability that occurs as a result of the inverse Landau damping for ion velocity. It is shown here that in a finite length system there exists another type of the ion sound instability which occurs for $v_0^2 < c_s^2$ and is a result of the wave coupling mediated by reflections from the walls. Analytical theory is developed [1] and is compared with results of direct initial value numerical simulations. Formally analogous model is applicable for the excitation of the lower-hybrid waves in Hall thruster [2]. It is expected that this mechanism of ion sound and lower hybrid instabilities may be operative in **E** × **B** plasma discharges in which the ion beam is created by the application of the external voltage.

[1]O. Koshkarov, A. I. Smolyakov, I. D. Kaganovich, and V. I. Ilgisonis, Ion sound instability driven by the ion flows, Phys. Plasmas **22**, 052113 (2015).
[2]A. Kapulkin and E. Behar, Ion Beam Instability in Hall Thrusters, IEEE Trans. Plasma Sci. **43**, 64 (2015).

HT6 9 What is the size of a floating sheath? An answer* FARINA VOIGT, SCHABNAM NAGGARY, RALF PETER BRINKMANN, *Institute for Theoretical Electrical Engineering, Ruhr-University Bochum* The formation of a non-neutral boundary sheath in front of material surfaces is universal plasma phenomenon. Despite several decades of research, however, not all related issues are fully clarified. In a recent paper, Chabert pointed out that this lack of clarity applies even to the seemingly innocuous question "What the size of a floating sheath?" [1] This contribution attempts to provide an answer that is not arbitrary: The size of a floating sheath is defined as the plate separation of an equivalent parallel plate capacitor. The consequences of the definition are explored with the help of a self-consistent sheath model, and a comparison is made with other sheath size definitions.

*Deutsche Forschungsgemeinschaft within SFB TR 87.

[1]Plasma Sources Sci. Technol. **23**, 065042 (2014).

HT6 10 Experimental Study of a Pulsating Anode Spot in Helium* BENJAMIN YEE, ED BARNAT, *Sandia National Laboratories* BRETT SCHEINER, SCOTT BAALRUD, *University of Iowa* MATT HOPKINS, *Sandia National Laboratories* Anode spots occur when a sufficiently small electrode is biased well above the plasma potential. Under these conditions, electrons are accelerated toward the electrode obtaining adequate energy to ionize the background gas near the face of the electrode. With a large enough bias, a threshold is exceeded causing the ionization region to rapidly expand into a high potential plasma encompassed by a double layer. While this secondary plasma can be stable, it is often observed to possess interesting dynamics. In this work, we examine a pulsating anode spot formed in helium above a solid electrode. Said spot exhibits no stable condition, but instead repeatedly forms and collapses with a frequency on the order of 10 kHz, varying with pressure and electron density. Higher frequency phenomena, on the order of 1 MHz, are also observed during the collapse of the spot. We consider several measurements of the spot properties in order to better understand the physics of its formation and collapse as well as the associated timescales.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under contracts DE-AC04-94SL85000 and DE-SC0001939.

HT6 11 Effects Of Secondary Electron Emission On The Plasma Sheath Of A Copper Wall* ADRIAN LOPEZ, JOHN FOSTER, *University of Michigan* Secondary electron emissions (SEE) from surfaces immersed in plasma such as that found in Hall thruster channels has the potential to affect not only the sheath potential distribution and overall sheath voltage, but also influence the near plasma properties. Such changes can influence engine performance and lifetime. In order to better understand how SEE can bring about changes in the bulk plasma, Langmuir probe-derived electron energy distribution measurements are made outside the sheath of a target under electron beam irradiation. Rather than numerically differentiating the I-V characteristic, an AC superimposed signal is used to obtain the electron energy distribution function (EEDF). This approach allows for better resolution of the distribution function, in particular, the distribution tail. In this manner, numerical noise and artificial structure that arises due to numerical differentiation can be avoided. EEDF changes are correlated with observed changes in the sheath potential of a copper substrate irradiated with a monoenergetic electron beam.

*Work supported by US Air Force grant FA9550-09-1-0695.

HT6 12 Observation of ExB effect on contact angle of incident deuterium ion at the graphite target of the weakly magnetized plasmas NAM-KYUN KIM, J. SONG, Y. JIN, K.-B. ROH, G.-H. KIM, *Seoul National University, Seoul, Korea* Many fusion researches have been considered that the ion incident angle at the first wall or the divertor surface is that of B-field line. Ahedo predicted that the ion motion should be influenced by the E-field near the plasma boundary, that is the E x B drift. To verify his prediction, the discrepancy between the ion incident angle and the angle of B-field line to the surface was investigated in this study. A weakly magnetized D_2 ECR plasma was used to investigate the ion incident angle. The ion incident angle was measured from a morphological change of a graphite target during ion irradiation, changing the B-field angle to the target surface. The B-field strength near the target was 700 gauss. Result reveals that the ion incident angle becomes 16° when the field angle is 85°, for example. The result is comparable with the estimation of the Ahedo's magnetic sheath model. With the model, it can be understood that the ion trajectory starts to deviate from the B-field line inside the presheath where the E-field start to increase. For the B-field strength of our device, however, the strong E-field inside the sheath accelerates ions only to the surface-normal direction, and no E x B drift occurs there. Details with a consideration of the B-field strength will be discussed.

HT6 13 GAS PHASE PLASMA CHEMISTRY

HT6 14 Mechanism of plasma-assisted ignition for H_2 and C1-C5 hydrocarbons ANDREY STARIKOVSKIY, *Princeton University* NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* Nonequilibrium plasma demonstrates 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. A new, validated mechanism for high-temperature hydrocarbon plasma assisted combustion was built and allows to qualitatively describe plasma-assisted combustion close and above the self-ignition threshold. The principal mechanisms of plasma-assisted ignition and combustion have been established and validated for a wide range of plasma and gas parameters. These results provide a basis for improving various energy-conversion combustion systems, from automobile to aircraft engines, using nonequilibrium plasma methods.

HT6 15 Effects of ROS and RNS in non-equilibrium plasma enhanced oxidizing and nitriding VITALY DATSYUK, *Taras Shevchenko National University of Kyiv* IGOR IZMAILOV, VADYM NAUMOV, *Institute of Semiconductor Physics, National Academy of Sciences of Ukraine* VLADIMIR KHOMICH, VYACHESLAV TSIOLKO, *Institute of Physics, National Academy of Sciences of Ukraine* Plasma enhanced oxidizing and nitriding processes are of great interest for physics and applications [1]. However, despite all advances in plasma technology, mechanisms of non-equilibrium plasma chemistry are not quite clear, particularly concerning reactive oxygen and nitrogen species (ROS/RNS) in metastable states. We tried to study this matter more detail. Experiments were done in a low temperature magnetron with a non-self-sustained glow discharge in oxygen/nitrogen/argon mixtures, employing electrical and optical diagnostics. Measurements showed that plasma processing is accompanied by the formation of electronically excited particles ROS/RNS. Computer modeling by using 0D-kinetic and 1D-fluid models including ionization, excitation, dissociation-recombination, vibrational relaxation, collisional quenching and radiation revealed the most probable mechanisms of plasma-chemical transformations. Effects of metastables of singlet oxygen O_2^*(a,b) and nitrogen N_2^*(A) as well as small but important radicals $O^*(^1D)$, $N^*(^2D)$ were also examined. Our study confirms the role of ROS/RNS in plasma kinetics and indicates the way toward more efficient oxygen and nitrogen plasma processing.

[1]M. A. Lieberman, A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, John Wiley & Sons, 2005.

HT6 16 PLASMA-SURFACE INTERACTIONS

HT6 17 Separated effects of ions, metastables and photons on the properties of barrier layers on polymers* BEATRIX BISKUP, MARC BOEKE, JAN BENEDIKT, ACHIM VON KEUDELL, *Ruhr-Universitaet Bochum* Analyses of a-C:H /a-Si:H multilayers on polymer substrates indicated that prolonged ion bombardment influences negatively the properties of the barrier layer, while a short plasma pretreatment can improve the barrier effect. This work is motivated by these results and investigates the influence of different reactive plasma components, namely ions, metastables and VUV-photons, on the properties of the grown barrier layer. To separate the different species and their influence on plasma pretreatment and film growth, we build a grid system, which repels the ions from the substrate, so that only metastables and VUV-photons have an effect on the layer. An integral part of this investigation is, to measure the photon fluxes to the substrate by an intensity calibrated VUV monochromator. For that, a differentially pumped monochromator with a spectral range 30 – 300 nm is used, where the two most prominent argon lines at 104.9 and 106.8 nm can be measured. In this approach we are able to study the different effects of the plasma species and also possible synergy effects, to improve the properties of the barrier layer.

*This work is supported by the DFG within the SFB-TR 87.

HT6 18 Composite layers for barrier coatings on polymers* MARKUS BROCHHAGEN, CHRISTOPH VORKOETTER, MARC BOEKE, JAN BENEDIKT, *Ruhr-Universitaet Bochum* Amorphous hydrogenated carbon (a-C:H), amorphous hydrogenated silicon (a-Si:H), and SiO2 thin films are of high interest because they can serve as a gas barrier on polymers. To understand how the coating changes the overall barrier properties of the thin film-polymer system, optical, mechanical, and barrier properties have to be studied. One of the important characteristic of such coatings is their compressive stress, which has beneficial as well as unwanted effects. The stress can cause deformation of the bulk material or de-lamination of the film. The mechanical stability can be improved and it is possible to reduce cracking due to elongation, as the compressive stress can compensate externally applied tensile strain. Stress and mechanical properties of composite layers can be manipulated directly by embedding nanoparticles in an amorphous matrix film. Therefore nanoparticles and amorphous layers are investigated before they can be assembled in a composite layer. Growth rates as well as optical and mechanical properties are explored in this work. An inductively coupled plasma source was used for all amorphous layers and the silicon nanoparticles with diameter around 5 nm were produced in a capacitively coupled plasma reactor.

*This work is supported by DFG within SFB-TR87.

HT6 19 Runaway Electron Preionized Diffuse Discharge and Its Impact on Plane Anode* VICTOR TARASENKO, *Head of laboratory* MICHAEL EROFEEV, *researcher* VASILII RIPENKO, *postdoctor* MIKHAIL SHULEPOV, *junior researcher* EVGENII BAKSHT, *senior researcher* NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY COLLABORATION,† INSTITUTE OF HIGH CURRENT ELECTRONICS COLLABORATION‡ The spatial structure of a runaway electrons preionized diffuse discharge (REP DD) in nonuniform electric field and the influence of its plasma on the surface of a plane anode have been studied. In our experiments, we used a NPG-18/3500N high-voltage generator. The incident voltage had negative polarity, amplitude of ~20 kV, and FWHM of 6 ns; the discharge current was up to 200 A. The discharge plasma was formed in nitrogen by applying high voltage pulses to the interelectrode gap which was varied between 2 and 9 mm. Under such conditions, the specific input power reached up to 10 MW/cm^3. It is established that diffuse channel is the initial stage of the discharge radiation; then anode spot, channel with high glow intensity based on the anode spot and spark channel are consecutively formed. Spark formation finished within 10–15 ns after the onset of the discharge. Microstructure of spark and diffuse channels with anode spot autograph have been detected. The traces of such discharge represents itself an aggregation of up to 100 microcraters with dimeters of 5–100 micrometers. It was also shown that diffuse discharge does not leave erosive action on an anode surface or on its carbon cover.

*This work was supported by the Russian Science Foundation under the Grant Number 14-29-00052.

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‡V. Tarasenko, M. Erofeev, V. Ripenko, M. Shulepov, E. Baksht.

HT6 20 PLASMA DIAGNOSTIC TECHNIQUES

HT6 21 Electric field strength determination in filamentary DBDs by CARS-based four-wave mixing PATRICK BOEHM, *Ruhr-University Bochum, Institute for Experimental Physics V* MANFRED KETTLITZ, RONNY BRANDENBURG, HANS HOEFT, *INP Greifswald* UWE CZARNETZKI, *Ruhr-University*

Bochum, Institute for Experimental Physics V The electric field strength is a basic parameter of non-thermal plasmas. Therefore, a profound knowledge of the electric field distribution is crucial. In this contribution a four wave mixing technique based on Coherent Anti-Stokes Raman spectroscopy (CARS) is used to measure electric field strengths in filamentary dielectric barrier discharges (DBDs). The discharges are operated with a pulsed voltage in nitrogen at atmospheric pressure. Small amounts hydrogen (10 vol%) are admixed as tracer gas to evaluate the electric field strength in the 1 mm discharge gap. Absolute values of the electric field strength are determined by calibration of the CARS setup with high voltage amplitudes below the ignition threshold of the arrangement. Alteration of the electric field strength has been observed during the internal polarity reversal and the breakdown process. In this case the major advantage over emission based methods is that this technique can be used independently from emission, e.g. in the pre-phase and in between two consecutive, opposite discharge pulses where no emission occurs at all. This work was supported by the Deutsche Forschungsgemeinschaft, Forschergruppe FOR 1123 and Sonderforschungsbereich TRR 24 "Fundamentals of complex plasmas".

HT6 22 Measurement of Electron Density Using the Multipole Resonance Probe, Langmuir Probe and Optical Emission Spectroscopy in Low Pressure Plasmas with Different Electron Energy Distribution Functions MORITZ OBERBERG, NIKITA BIBINOV, STEFAN RIES, PETER AWAKOWICZ, *Ruhr-University Bochum* INSTITUTE OF ELECTRICAL ENGINEERING AND PLASMA TECHNOLOGY TEAM In recently publication [1], the young diagnostic tool Multipole Resonance Probe (MRP) for electron density measurements was introduced. It is based on active plasma resonance spectroscopy (APRS). The probe was simulated und evaluated for different devices. The geometrical and electrical symmetry simplifies the APRS model, so that the electron density can be easily calculated from the measured resonance. In this work, low pressure nitrogen mixture plasmas with different electron energy distribution functions (EEDF) are investigated. The results of the MRP measurement are compared with measurements of a Langmuir Probe (LP) and Optical Emission Spectroscopy (OES). Probes and OES measure in different regimes of kinetic electron energy. Both probes measure electrons with low kinetic energy (<10 eV), whereas the OES is influenced by electrons with high kinetic energy which are needed for transitions of molecule bands. By the determination of the absolute intensity of N_2(C-B) and N_2^+(B-X) electron temperature and density can be calculated. In a non-maxwellian plasma, all plasma diagnostics need to be combined.

[1]C. Schulz *et al.*, IEEE Sensors Journal **14** (2014).

HT6 23 Probe measurements of electron energy spectrum in Helium/air micro-plasma at atmospheric pressure* V. I. DEMIDOV, *AFRL, WVU* S. F. ADAMS, J. A. MILES, *AFRL* M. E. KOEPKE, *WVU* I. P. KURLYANDSKAYA, *INTEPH Technologies LLC* A. L. HENSLEY, B. A. TOLSON, *UES Inc.* It is experimentally demonstrated that a wall probe may be a useful instrument for interpretation of electron energy spectrum in a micro-plasma with a nonlocal electron distribution function at atmospheric pressure. Two micro-plasma devices were fabricated with three layers of molybdenum metal foils with thickness of 0.1 mm separated by two sheets of mica insulation with thickness of 0.11 mm. In one device a hole with the diameter of 0.2 mm formed a cylindrical discharge cavity that passed through the entire five layers. In the second device the hole has the diameter of 0.065 mm. In both devices the inner molybdenum layer formed a wall probe, while the outer layers of molybdenum served as the hollow cathode and anode. The discharge was open into air with flow of helium gas. It is found that the wall probe I-V trace is sensitive to the presence of helium metastable atoms. The first derivative of the probe current with respect to the probe potential shows peaks revealing fast electrons at specific energies arising due to plasma chemical reactions. The devices may be applicable for developing analytical sensors for extreme environments, including high radiation and vibration levels and high temperatures.

*This work was performed while VID held a NRC Research Associateship Award at AFRL.

HT6 24 Time Resolution of Electron Density Measurement using Mach Zehnder Interferometer in Arc Discharge Plasma TAKAFUMI YAMADA, MAKOTO MATSUI, *Shizuoka Univ* Sample return mission from Jupiter Trojans is proposed for future mission in JAXA. Reentry velocity in this mission is estimated at 14 kilometers per second. Although an accurate estimation of radiation heating is required when reentry velocity is very high, it is reported that there is discrepancy between predicts and experimental results. Precursor photoionization is considered as the causation of it, and measurement of electron density over ahead of strong shock waves to behind of is acquired for figuring out this discrepancy. In this study, the goal is construction of Mach-Zehnder interferometer which is applicable to hyper velocity shock waves and is acquirable to electron density distribution in them. First, a plasma source has been developed for a measuring object. In addition, the interferometer will be applied to measure electron density.

HT6 25 Measuring atomic oxygen densities and electron properties in an Inductively Coupled Plasma for thin film deposition* DAVID MEEHAN, *York Plasma Institute, University of York* ANDREW GIBSON, *York Plasma Institute, University of York and Laboratoire de Physique des Plasmas, Ecole Polytechnique* JEAN-PAUL BOOTH, *Laboratoire de Physique des Plasmas, Ecole Polytechnique* ERIK WAGENAARS, *York Plasma Institute, University of York* Plasma Enhanced Pulsed Laser Deposition (PE-PLD) is an advanced way of depositing thin films of oxide materials by using a laser to ablate a target, and passing the resulting plasma plume through a background Inductively-Coupled Plasma (ICP), instead of a background gas as is done in traditional PLD. The main advantage of PE-PLD is the control of film stoichiometry via the direct control of the reactive oxygen species in the ICP instead of relying on a neutral gas background. The aim is to deposit zinc oxide films from a zinc metal target and an oxygen ICP. In this work, we characterise the range of compositions of the reactive oxygen species achievable in ICPs; in particular the atomic oxygen density. The density of atomic oxygen has been determined within two ICPs of two different geometries over a range of plasma powers and pressures with the use of Energy Resolved Actinometry (ERA). ERA is a robust diagnostic technique with determines both the dissociation degree and average electron energy by comparing the excitation ratios of two oxygen and one argon transition. Alongside this the electron densities have been determined with the use of a hairpin probe.

*This work received financial support from the EPSRC, and York-Paris CIRC.

HT6 26 Quantitative measurement of VUV radiation related to polymer pre-treatment in a microwave driven low pressure plasma* FELIX MITSCHKER, ENRIQUE IGLESIAS, MARCEL FIEBRANDT, NIKITA BIBINOV, PETER AWAKOWICZ, *Ruhr-University Bochum* INSTITUTE FOR ELECTRICAL ENGINEERING AND PLASMA TECHNOLOGY TEAM Plasma pre-treatment of polymers is used for a wide range of applications, e.g. prior to deposition of thin SiO_x barrier films. At this, plasma generated particles and vacuum ultraviolet (VUV) radiation can reach the polymer surface. Both have a severe impact on the polymer interface, resulting in the production of e.g. dangling bonds. These modifications govern subsequent thin film growth. For understanding of pre-treatment processes, VUV radiation has to be quantified. Absolute VUV photon fluences are determined in situ, at the substrate holder, applying sodium salicylate (NaSal) as a scintillator. Therefore, VUV photons are quantified from 50 nm to 325 nm, due to constant quantum efficiency of NaSal, as integrals over defined wavelength ranges (50-110, 110-170, 170-200 and 200-325 nm). The set up allows for measurement with three scintillators. Each is equipped with optical filters. Observation of the fluorescence band is performed by means of optical fibers and a photomultiplier. Quantification is achieved by simultaneous measurement with an absolutely calibrated echelle spectrometer in the spectral range from 200 nm to 325 nm, taking into account observed plasma volumes. VUV photons are quantified for argon and oxygen plasmas as well as mixtures of both.

*Support by the German Research Foundation (DFG) within the framework of the SFB TRR 87/1 is acknowledged.

HT6 27 Developing a diagnostic tool for measuring maximum effective temperature within high pressure electrodeless discharges MICHAEL WHITING, BARRY PRESTON, STUART MUCKLEJOHN, MONICA SANTOS, GRAEME LISTER, *Ceravision Limited* Here we present an investigation into the feasibility of creating a diagnostic tool for obtaining maximum arc temperature measurements within a high pressure electrodeless discharge; utilizing integrating sphere measurements of optically thin lines emitted from mercury atoms within commercially available high pressure mercury lamp arc tubes. The optically thin lines chosen were 577 nm and 1014 nm from a 250 W high pressure mercury lamp operated at various powers. The effective temperature could be calculated by considering the relative intensities of the two optically thin lines and comparison with the theoretical ratio of the temperature dependent power emitted from the lines derived from the atomic spectral data provided by NIST. The calculations gave effective arc temperatures of 5755, 5804 and 5820 K at 200, 225, 250 W respectively. This method was subsequently used as a basis for determining maximum effective arc temperature within microwave-driven electrodeless discharge capsules, with varying mercury content of 6.07, 9.4 and 12.95 mg within $1\times 10^{-6}\ m^3$ giving maximum effective temperatures of 5163, 4768 and 4715 K respectively at ~240 W.

HT6 28 Damage development of gallium nitride under plasma exposure DAISUKE OGAWA, YOSHITSUGU BANNO, YOSHITAKA NAKANO, KEIJI NAKAMURA, *Chubu University* Plasma damage has been focused on since 1990s. In this era, this issue was manly targeted onto silicon-based semiconductors. However, since the gallium nitride (GaN) was paid attentions to after blue LEDs, they start to consider the damages given to GaN as well. We have so far utilized photoluminescence (PL) emission from the surface of GaN film to monitor the evolution of damage given by plasma exposure. This measurement gives us clues how plasma exposure changed intermediate electronical states in the film without taking the film out of the chamber. First of all, we analyzed the development of damage given by argon plasma, which is one of the most fundamental plasma to analyze. Argon plasma is responsible to give only physical damages over a GaN film. Our PL measurements showed a significant decrease within approximately 10 seconds after the plasma exposure started. This means that ions and radiations created from the plasma gives significant damages to the GaN film even short period of time. Chlorine-related gas is normally utilized for chemical etching. Chlorine species realize continuous damage layer removals, but some reports already mentioned that the processed device has difference electrical properties after the plasma exposure. In this presentation, we will show what happens to GaN film after the plasma exposure in terms of crystal structure and impurities of GaN, by connecting PL emission and ex-situ measurements.

HT6 29 Time-resolved probe measurement in pulsed plasma using advanced boxcar technique DONG-HWAN KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University* HYUN-JU KANG, JUN-HYEON MOON, *Department of Electrical Engineering, Hanyang University* MOO-YOUNG LEE, *Department of Nanoscale Semiconductor Engineering, Hanyang University* SEYEOL PAEK, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* JINYOUNG BANG, *Memory E Technology Team, Samsung Electronics* A novel plasma diagnostic method based on boxcar technique is developed for time-resolved measurement of electron energy distribution function (EEDF) in pulsed plasma. Pulsed plasma have been used for many applications including etching and deposition in semiconductor manufacturing because the pulsed plasma reduces the plasma induced damage (PID). In order to understand underlying physics of the pulsed plasma, probe measurement based on boxcar theory have been performed. However, in conventional method, measurement time is very long (over an hour for measurement of 1 kHz pulsed plasma), and displacement current, generated due to use of impulse voltage, can result in significant inaccuracy of EEDF especially in low density plasma. In this work, a novel method using sequential switching of dc voltage and reconstruction of measured current is proposed; the detail procedures were mentioned by Godyak and Alexandrovich (Proceeding of XXVIIth ICPIG, 2005). This method reduces the time required for the measurement to a few minutes, and there is not influence of the displacement current, resulting in reliable measurement of EEDF. Using this method, well-known characteristics in active and after-glow of the pulsed plasma are well observed.

HT6 30 High time-resolution spatial distribution measurement of the ion flux and the electron temperature in an inductively coupled pulse plasma JIHWAN PARK, MOOYOUNG LEE, DONGHWAN KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University* CHINWOOK CHUNG, *Department of Electrical Engineering, Hanyang University* The time-resolved spatial distribution of the plasma parameters are measured in the pulse-modulated inductively coupled argon discharge. During the initial active-glow period, the ion flux and the electron temperature beneath the antenna are higher than the center of the reactor. While the plasma is approaching a steady state active-glow, the spatial distributions of the ion flux and the electron temperature evolve a center-high profile. After the pulse is off, both the ion flux and the electron temperature are decreased maintaining their center-high profile. At the bottom surface, on the other hand, the center-high distribution profile is observed from the beginning of the active-glow, and maintained during the after-glow period. Compared to the continuous wave discharge, the spatial uniformity of the plasma parameters is improved during the active-glow period, and it is increased with the increasing pulse frequency. These spatial distribution characteristics can be explained by the discharge mechanism and the diffusion of charged particles, and it should be considered to achieve desirable process results in the pulse-modulated plasma material processing.

HT6 31 Helium temperature measurements in a hot filament magnetic mirror plasma using high resolution Doppler spectroscopy S. KNOTT, P.J. MCCARTHY, A.A. RUTH, *University College Cork* Langmuir probe and spectroscopic diagnostics are used to routinely measure electron temperature and density over a wide operating range in a reconfigured Double Plasma device at University College Cork, Ireland [1]. The helium plasma, generated through thermionic emission from a negatively biased tungsten filament, is confined by an axisymmetric magnetic mirror configuration using two stacks of NdFeB permanent magnets, each of length 20 cm and diameter 3 cm placed just outside the 15 mm water cooling jacket enclosing a cylindrical vacuum vessel of internal diameter 25 cm. Plasma light is analysed using a Fourier Transform-type Bruker spectrometer with a highest achievable resolution of 0.08 cm^{-1}. In the present work, the conventional assumption of room temperature ions in the analysis of Langmuir probe data from low temperature plasmas is examined critically using Doppler spectroscopy of the 468.6 nm He II line. Results for ion temperatures obtained from spectroscopic data for a variety of engineering parameters (discharge voltage, gas pressure and plasma current) will be presented.

[1]P. J. Mc Carthy *et al.*, 30th ICPIG, Belfast, 2011.

HT6 32 Optical emission spectroscopy of 'spokes' in a high power impulse magnetron discharge* JULIAN HELD, ANTE HECIMOVIC, VOLKER SCHULZ-VON DER GATHEN, *Ruhr University Bochum* Localized regions of intense light emission can be observed in front of the target of a high power impulse magnetron sputtering (HiPIMS) discharge. These regions are often referred to as 'spokes' and have been observed to rotate in E x B direction with frequencies in the order of 100 kHz. The spokes are located close to the target inside the zone of magnetic confinement where the magnetic field lines are closed. Outside this zone, the HiPIMS discharge has already been investigated thoroughly by the community using Langmuir probes. However, inside this zone a probe would change the magnetic field and disturb the discharge. In this work, the spokes are therefore investigated using optical emission spectroscopy. A high resolution plane grating spectrograph combined with a fast, gated, intensified CCD camera is employed to analyse the discharge. Line broadening of the Balmer series of atomic hydrogen is studied by adding a small admixture of hydrogen to the argon used as the working gas. Additionally, the influence of reactive admixtures on the discharge, such as nitrogen or oxygen, is investigated.

*Supported by the DFG in SFB TR-87.

HT6 33 A computational study of the plasma-flow interplay in a reverse vortex microwave discharge for CO_2 conversion VINCENT VERMEIREN, ANNEMIE BOGAERTS, *PLASMANT University of Antwerp* PLASMANT UNIVERSITY OF ANTWERP TEAM The problem of global warming due to greenhouse gas emission is one of the most prominent and urgent problems of the 21st century. Recently, surface wave produced plasmas, created by a microwave discharge, have shown to be very efficient in the conversion of the main emitted greenhouse gas, namely CO_2. This is the result of a high thermodynamic inequilibrium in which the CO_2 is efficiently dissociated through vibrational excitation. Very promising results have been obtained in experiments using a reverse vortex gas flow [1]. Although it is known that reverse vortex gas flows tend to create a pressure and temperature drop in the center, it is unclear which effect the flow and the plasma have on each other. In this study we model this interplay between the reverse vortex gas flow and the plasma, to get a deeper understanding of the underlying processes. As a first step, Argon gas is used due to its simpler chemistry, limiting the computational costs. In a next step, a reduced chemistry set of CO_2 will be implemented.

[1]W. A. Bongers *et al.*, ISPC (2015).

HT6 34 Higher order moment models of electron transport in gases and liquids NATHAN GARLAND, GREGORY BOYLE, DANIEL COCKS, *Physical Sciences, College of Science and Engineering, James Cook University* SASA DUJKO, *Gaseous Electronics Laboratory, Institute of Physics, University of Belgrade* RONALD WHITE, *Physical Sciences, College of Science and Engineering, James Cook University* This study seeks to extend an existing higher order (four) moment model to consider electron transport in gases and liquids. The impact of coherent scattering and other liquid effects are included into the moment model. By reconciling existing closure approximations into a new closure assumption, the subsequent moment model will be studied to understand the accuracies and sensitivities of various closure assumptions used in practice. A particular focus is the ability of the higher order moment model to treat spatially varying electric fields including interfaces, through comparison of the results with a space-time dependent solution of Boltzmann's equations.

HT6 35 On judgement of electron transfer between two regions divided by the separatrix of confronting divergent magnetic fields applied to an inductively coupled plasma* HIROTAKE SUGAWARA, TAPPEI YAMAMOTO, *Hokkaido University* In order to quantitatively evaluate the electron confinement effect of the confronting divergent magnetic fields (CDMFs) applied to an inductively coupled plasma [1], we analyzed the electron transfer between two regions divided by the separatrix of the CDMFs in Ar at 0.67 Pa at 300 K using a Monte Carlo method. A conventional transfer judgement was simply based on the electron passage across the separatrix from the upstream source region to the downstream diffusion region. An issue was an overestimation of the transfer due to temporary stay of electrons in the downstream region. Electrons may pass the downstream region during their gyration even in case they are effectively bound to the upstream region, where their guiding magnetic flux lines run. More than half of the transfers were temporary ones and such seeming transfers were relevantly excluded from the statistics by introducing a newly chosen criterion based on the passage of electron gyrocenters across the separatrix and collisional events in the downstream region. Simulation results showed a tendency that the ratio of the temporary transfers excluded was higher under stronger magnetic fields because of higher cyclotron frequency.

*Work supported by JSPS Kakenhi Grant Number 16K05626.

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

HT6 36 The Generalized Onsager Model and DSMC Simulations of High-Speed Rotating Flow with Swirling Feed DR. SAHADEV PRADHAN, *Dept. of Chemical Engineering, Indian Institute of Science, Bangalore-560 012, India* The generalized Onsager model for the radial boundary layer and of the generalized Carrier-Maslen model for the axial boundary layer at the end-caps in a high-speed rotating cylinder [1], are extended to incorporate the angular momentum of the feed gas for a swirling feed for single component gas and binary gas mixture. For a single component gas,

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the analytical solutions are obtained for the sixth-order generalized Onsager equations for the master potential, and for the fourth-order generalized Carrier-Maslen equation for the velocity potential. In both cases, the equations are linearized in the perturbation to the base flow, which is a solid-body rotation. The equations are restricted to the limit of high Reynolds number and (length/radius) ratio, but there is no limitation on the stratification parameter. The linear operators in the generalized Onsager and generalized Carrier-Maslen equations with swirling feed are still self-adjoint, and so the eigenfunctions form a complete orthogonal basis set. The analytical solutions are compared with direct simulation Monte Carlo (DSMC) simulations. The comparison reveals that the boundary conditions in the simulations and analysis have to be matched with care. When these precautions are taken, there is excellent agreement between analysis and simulations, to within 15%.

[1]S. Pradhan and V. Kumaran, J. Fluid Mech. **686**, 109 (2011); V. Kumaran and S. Pradhan, J. Fluid Mech. **753**, 307 (2014).

HT6 37 The generalized Onsager model and DSMC simulations of high-speed rotating flows with product and waste baffles DR. SAHADEV PRADHAN, *Dept of Chemical Engineering, Indian Institute of Science, Bangalore-560 012, India* The generalized Onsager model for the radial boundary layer and of the generalized Carrier-Maslen model for the axial boundary layer in a high-speed rotating cylinder [1], are extended to a multiply connected domain, created by the product and waste baffles. For a single component gas, the analytical solutions are obtained for the sixth-order generalized Onsager equations for the master potential, and for the fourth-order generalized Carrier-Maslen equation for the velocity potential. In both cases, the equations are linearized in the perturbation to the base flow, which is a solid-body rotation. An explicit expression for the baffle stream function is obtained using the boundary layer solutions. These solutions are compared with direct simulation Monte Carlo (DSMC) simulations and found excellent agreement between the analysis and simulations, to within 15%, provided the wall-slip in both the flow velocity and temperature are incorporated in the analytical solutions.

[1]S. Pradhan and V. Kumaran, J. Fluid Mech. **686**, 109 (2011); V. Kumaran and S. Pradhan, J. Fluid Mech. **753**, 307 (2014).

HT6 38 Simulation for spatio-temporal variation of chemically active species in an atmospheric pressure streamer discharge. ATSUSHI KOMURO, KAZUNORI TAKAAHSHI, AKIRA ANDO, *Department of electrical engineering, Tohoku University* Spatiotemporal variation of radical density in an atmospheric pressure plasma discharge has been investigated by two-dimensional numerical simulation. Behaviors of radicals are characterized by four areas as "Hot anode region", "Secondary streamer region", "Primary streamer region", and "Near-cathode region". Although the reduced electric field in "Hot anode region" is relatively high, the gas temperature also increases and the ozone destruction process proceed. On the other hand, in "Near-cathode region", the high-energy radicals such as N(4S) is effectively produced because the instantaneous value of reduced electric field is high. Behaiviour of OH is also investigated. The results show that OH is effectively produced in "Secondary streamer region" and is not effective in "Hot anode region". This is because the reduced electric filed in "Secondary streamer region" is sufficiently high for the dissociation of H2O by O(D) and N2(a) and the gas temperature in "Hot anode region" is too high for the production of OH.

HT6 39 Escape factors for Paschen 2p-1s lines in Ar, Kr, and Xe plasmas XI-MING ZHU, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, Bochum 44780, Germany* ZHI-WEN CHENG, YI-KANG PU, *Department of Engineering Physics, Tsinghua University, Beijing 100084, People's Republic of China* Radiation trapping is often observed when investigating low-temperature plasmas. Photons emitted from an upper state may be reabsorbed by a lower state before they leave the plasmas. To account for this effect, the "escape factor" as a function of optical depth is often adopted. In previous works several simple expressions of the escape factor were proposed for uniform plasmas with emission line profiles dominated by Doppler broadening and without line splitting due to hyperfine structure. These assumptions are valid for atoms e.g. Ar in uniform discharges. However, the excited state density in many low-temperature plasmas is non-uniform and the emission line profile can be influenced by collisional broadening. In this work, we study the escape factors of Paschen 2p-1s lines of Ar, Kr, and Xe in non-uniform plasmas. The collisional broadening and the hyperfine structure for Kr and Xe lines are both included. The calculated escape factor expression is verified particularly by an experiment in a low-pressure discharge. The escape factor equation for high- to atmospheric-pressure discharges is also provided.

HT6 40 Planar Multipol-Resonance-Probe: A Spectral Kinetic Approach MICHAEL FRIEDRICHS, *Institute of Product and Process Innovation, Leuphana University Lüneburg* JUNBO GONG, RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum* JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lüneburg* SEBASTIAN WILCZEK, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum* Measuring plasma parameters, e.g. electron density and electron temperature, is an important procedure to verify the stability and behavior of a plasma process. For this purpose the multipole resonance probe (MRP) represents a satisfying solution to measure the electron density. However the influence of the probe on the plasma through its physical presence makes it unattractive for some processes in industrial application. A solution to combine the benefits of the spherical MRP with the ability to integrate the probe into the plasma reactor is introduced by the planar model of the MRP (pMRP). Introducing the spectral kinetic formalism leads to a reduced simulation-circle compared to particle-in-cell simulations. The model of the pMRP is implemented and first simulation results are presented.

HT6 41 A progress report on the LXCat project* SERGEY PANCHESHNYI, *ABB Corporate Research* LEANNE PITCHFORD, *LAPLACE, CNRS and University of Toulouse* LXCat is an open-access, web-based platform (www.lxcat.net) for storing, exchanging and manipulating data for modeling the electron and ion components of low-temperature, non-equilibrium plasmas. The data types supported by LXCat are electron and ion scattering cross sections and rate coefficients, electron and ion swarm/transport parameters, ion-neutral interaction potentials, and optical oscillator strengths. On-line tools allow for searching, graphical display, and downloading of data, and an on-line Boltzmann solver allows users to calculate electron transport and rate coefficients in arbitrary gas mixtures if "complete" sets of cross sections for the individual components are available in the databases. At present, 24 public databases contributed by different groups around the world can be accessed on LXCat. The database contributors retain ownership and are responsible for the contents and maintenance of the individual databases. New contributors are welcome and can request an account and receive instructions for setting up a password-protected database on LXCat. This presentation will summarize the LXCat project objectives, its structure, the available databases, and the current status of the project.

*Presented on behalf of the LXCat Team.

HT6 42 Sputtering, Plasma Chemistry, and RF Sheath Effects in Low-Temperature and Fusion Plasma Modeling* THOMAS G. JENKINS, SCOTT E. KRUGER, JAMES M. MCGUGAN, ALEXEI Y. PANKIN, CHRISTINE M. ROARK, DAVID N. SMITHE, PETER H. STOLTZ, *Tech-X Corporation* A new sheath boundary condition [1] has been implemented in VSim, a plasma modeling code which makes use of both PIC/MCC and fluid FDTD representations. It enables physics effects associated with DC and RF sheath formation - local sheath potential evolution, heat/particle fluxes, and sputtering effects on complex plasma-facing components - to be included in macroscopic-scale plasma simulations that need not resolve sheath scale lengths. We model these effects in typical ICRF antenna operation scenarios on the Alcator C-Mod fusion device, and present comparisons of our simulation results with experimental data together with detailed 3D animations of antenna operation. Complex low-temperature plasma chemistry modeling in VSim is facilitated by MUNCHKIN, a standalone python/C++/SQL code that identifies possible reaction paths for a given set of input species, solves 1D rate equations for the ensuing system's chemical evolution, and generates VSim input blocks with appropriate cross-sections/reaction rates. These features, as well as principal path analysis (to reduce the number of simulated chemical reactions while retaining accuracy) and reaction rate calculations from user-specified distribution functions, will also be demonstrated.

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

[1]Jenkins and Smithe, PSST **24**, 015020 (2015).

HT6 43 Comparison of initial seed electron generation mechanisms in kinetic simulations of positive streamers* CHRISTOPHER MOORE, ANDREW FIERRO, ROY JORGENSON, LAURA BIEDERMANN, PAUL CLEM, HAROLD HJALMARSON, MATTHEW HOPKINS, RAYMOND MARTINEZ, *Sandia Natl Labs* Positive streamer simulations typically resort to initiation by artificially seeding a small region with an initial plasma. However, in order to simulate observed variations in breakdown voltages and times in pulsed voltage experiments [1], a more physical model for the generation of the initial plasma/electrons is necessary. This work will investigate several models of generating the initial seed plasma in an air-filled gap with a dielectric present: a "typical" artificial initial plasma, ionization of the background air due to cosmic rays, field emission from the dielectric, and simulation of radiation incident on surfaces prior to applying the voltage resulting in diffuse e^- and O_2^- densities. 2D axisymmetric PIC-DSMC simulations using a detailed e^--air collision model including field-dependent detachment and photon transport [2] will be compared to experiments of an air gap with a dielectric cylinder and a 10 GV/s applied potential [1].

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

[1]L. B. Biedermann *et al., Dielectric-Directed Surface Flashover under Atmospheric Conditions*, PPC-O-2-6, 2015.

[2]C. H. Moore *et al., Development of PIC-DSMC Air Breakdown Model in the Presence of a Dielectric*, 43rd IEEE ICOPS, June 19-23, 2016.

HT6 44 A new approach to fluid modeling of Resistive Plate Chambers SASA DUJKO, DANKO BOSNJAKOVIC, ZORAN PETROVIC, *Institute of Physics, University of Belgrade, Serbia* We present a 1.5-dimensional model of Resistive Plate Chambers (RPCs) which are used for timing and triggering purposes in many high energy physics experiments. The model is based solely on the hydrodynamic approximation and assumes that the electron collisional source term in the continuity equation can be expanded in terms of gradients of the electron number density. Transport data used in this model are calculated using Monte Carlo simulations and a multi term solution of the Boltzmann equation. The model is employed to study the avalanche to streamer transition in RPCs under the influence of space charge effects and photoionization. In addition, this model is also used to calculate the average induced signals for different RPC configurations and applied electric field strengths. The results are compared with those obtained by classical fluid model with flux or bulk transport data as input parameters. Depending on the specific RPC configuration and applied electric field, the results for the induced charges calculated using these fluid models can differ as much as several hundred percents.

HT6 45 Complementary approaches to model an RF plasma jet at atmospheric pressure* F. SIGENEGER, J. SCHÄFER, D. LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* A nonthermal plasma jet has been investigated by three complementary model approaches. The argon jet consists of two concentric capillaries and two cylindrical electrodes driven by an RF voltage at 27.12 MHz. Investigations of a single filament in the active zone between both capillaries by means of a two-dimensional phase-resolved fluid model yields spatial profiles The heating profile deduced from this approach is used for a comprehensive description of the jet including gas flow and reactions of precursor molecules as well as their transport in the effluent. The obtained radial profiles of particle fluxes of precursor fragments onto the substrate qualitatively agree with measured The third model is devoted to the phenomena of self-organization observed e.g. in the regular azimuthal rotation of the filaments. Using the heating profile from the first approach, a three-dimensional hydrodynamic model of gas flow and heating is used to reveal the relation between the inclination of the filaments and the azimuthal gas velocity component.

*The work has been partly supported by the German Research Foundation (DFG) within SFB TRR 24.

HT6 46 Comparative Study in Stabilization Methods for Capacitively Coupled Plasma Simulation Using Finite Element Method HYONU CHANG, *Plasma Technology Research Center, National Fusion Research Institute* PLASMA FUNDAMENTAL TECHNOLOGY RESEARCH TEAM TEAM Many cases of hydrodynamic plasma analysis solve continuity equation for charged particles and energy balance equation for electron temperature adopting drift-diffusion approximation. In the transient convection-diffusion equation, finite element (FE) and finite difference schemes are unstable when convective term dominates diffusive term. In capacitively coupled plasma (CCP) cases, numerical instability is unavoidable due to enormous convection induced from the high electric field near the electrode. Several numerical stabilization methods have been developed to overcome this kind of instability problem in finite element scheme. Each of discontinuous Galerkin method (DGM), Petrov-Galerkin method (PGM) and characteristic Galerkin method (CGM) which are the developed stabilization methods, are applied to two-dimensional FE fluid code and suitability for CCP model is investigated.

HT6 47 Simulation of protons energy relaxation in electron gas by molecular dynamics method* ANDREY BOBROV, SERGEY BRONIN, SERGEY MAIOROV, EDUARD MANYKIN, BORIS B. ZELENER, BORIS V. ZELENER, *Joint Institute for High Temperatures of the Russian Academy of Sciences* Our work is concerned with simulation of heavy charged particles energy relaxation in electron gas. The research was stimulated by antihydrogen experiments that are held in conditions far from conditions of well studied nuclear fusion or gas discharge experiments. We used numerical simulation as a tool to test existing theoretical approaches to classical Coulomb system kinetics. By means of molecular dynamics method we calculated dynamics of energy relaxation of protons in ultracold electron gas. We considered non neutral plasma when number of electrons is much greater than the number of protons. We have shown that boundary conditions have significant influence on simulation results. Two types of boundary conditions were considered — periodic boundary conditions and reflecting walls. The influence of number of particles in the simulation cell was studied. The problem of Coulomb potential modification on small distances was also considered. Simulations were performed for electron densities 10^8 cm^{-3}, initial temperatures for electrons is equal 10 K and for protons 100 K.

*The work was supported by Russian Science Foundation grant RNF 14-19-01492.

HT6 48 A collisional-radiative model for low-pressure weakly magnetized Ar plasmas XI-MING ZHU, TSANKO TSANKOV, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, Bochum 44780, Germany* OLEKSANDR MARCHUK, *Institut für Energie- und Klimaforschung, Plasmaphysik, Forschungszentrum Jülich GmbH, Jülich 52425, Germany* Collisional-radiative (CR) models are widely investigated in plasma physics for describing the kinetics of reactive species and for optical emission spectroscopy. This work reports a new Ar CR model used in low-pressure (0.01–10 Pa) weakly magnetized (<0.1 Tesla) plasmas, including ECR, helicon, and NLD discharges. In this model 108 realistic levels are individually studied, i.e. 51 lowest levels of the Ar atom and 57 lowest levels of the Ar ion. We abandon the concept of an "effective level" usually adopted in previous models for glow discharges. Only in this way the model can correctly predict the non-equilibrium population distribution of close energy levels. In addition to studying atomic metastable and radiative levels, this model describes the kinetic processes of ionic metastable and radiative levels in detail for the first time. This is important for investigation of plasma-surface interaction and for optical diagnostics using atomic and ionic line-ratios. This model could also be used for studying Ar impurities in tokamaks and astrophysical plasmas.

HT6 49 Streamer propagation in air near and on curved dielectrics* ANNA DUBINOVA, UTE EBERT, *Centrum Wiskunde & Informatica* We simulate propagation of a positive streamer in air around a curved dielectric with a pronounced shading effect. In our setup a positive streamer is launched at the tip of a pin anode and propagates towards a grounded plate cathode. On the way of the streamer propagation path we place a curved dielectric body (e.g., a dielectric ball) of a diameter larger than the streamer diameter. This obstacle makes a streamer move around it. At the corner of the dielectric a surface streamer has a choice of moving along the surface or moving away from it. We explore physical mechanisms that can force a surface streamer to move all the way around a curved dielectric in air and nitrogen-oxygen mixtures. The potential candidates are secondary electron emission such as photoemission or field emission, higher dielectric permittivity, surface charge, lack of photoionization (in pure nitrogen). The problem is relevant for high-voltage technology, where surface streamers are often to be avoided.

*This research is supported by ABB Corporate Research.

HT6 50 Development of hybrid computer plasma models for different pressure regimes* JAKUB HROMADKA, TOMAS IBEHEJ, RUDOLF HRACH, *Department of Surface and Plasma Science, Faculty of Mathematics and Physics, Charles University in Prague* With increased performance of contemporary computers during last decades numerical simulations became a very powerful tool applicable also in plasma physics research. Plasma is generally an ensemble of mutually interacting particles that is out of the thermodynamic equilibrium and for this reason fluid computer plasma models give results with only limited accuracy. On the other hand, much more precise particle models are often limited only on 2D problems because of their huge demands on the computer resources. Our contribution is devoted to hybrid modelling techniques that combine advantages of both modelling techniques mentioned above, particularly to their so-called iterative version. The study is focused on mutual relations between fluid and particle models that are demonstrated on the calculations of sheath structures of low temperature argon plasma near a cylindrical Langmuir probe for medium and higher pressures. Results of a simple iterative hybrid plasma computer model are also given.

*The authors acknowledge the support of the Grant Agency of Charles University in Prague (project 220215).

HT6 51 GLOWS: DC, PULSED, MICROWAVE AND OTHERS

HT6 52 Current gain of a pulsed dc discharge in low-pressure gases VALERIY LISOVSKIY, *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine* POLINA OGLOBLINA, *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal* STANISLAV DUDIN, VLADIMIR YEGORENKOV, ALEXANDER DAKHOV, *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine* Current and voltage waveforms of a pulsed gas discharge have been measured in a wide frequency range (20 to 300 kHz) for the two pressure values of 0.1 and 1 Torr using four different technology-relevant gases: nitrogen, oxygen, carbon tetrafluoride and sulfur hexafluoride. It is shown that the current can be substantially increased in the pulsed dc discharge, especially with electronegative gases, as compared with the discharge current relating to the same but constant voltage. The maximum 9-fold current gain is obtained with sulfur hexafluoride. Carbon tetrafluoride furnishes up to 4-fold gain, while nitrogen and oxygen show the typical current gain of 1–2. We suggest the physical explanation of the current gain phenomenon in the pulsed discharge according to which the current gain at the start of the plasma phase of the pulsed discharge is observed due to the diffusion filling of the cathode sheath with charged particles in the afterglow phase. The current gain increase in electronegative gases is attributed to the slower plasma decay rate in this case because of the lower value of the ambipolar diffusion coefficient in the plasma with negative ions.

HT6 53 Applicability of the Child-Langmuir laws versions for describing the glow discharge cathode sheath in CO_2 VALERIY LISOVSKIY, HENNADII KROL, RUSLAN OSMAYEV, VLADIMIR YEGORENKOV, *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine* This work is devoted to the determination of the law that may be applicable to the description of the cathode sheath in CO_2. To this end three versions of the Child-Langmuir law have been considered – a collision free one (for the ions moving through a cathode sheath without collisions with gas molecules) as well as two collision- related versions– one for a constant mean free path of positive ions and one for a constant mobility of positive ions. The current-voltage characteristics and the cathode sheath thickness of the glow discharge in carbon oxide have been simultaneously measured in the pressure range from 0.05 to 1 Torr and with the discharge current values up to 80 mA. The interelectrode distance has been chosen such that the discharge consists only of the cathode sheath and a small portion of the negative glow, i.e. the experiments have been performed in short tubes. In this case the voltage drop across the cathode sheath is equal approximately to the voltage drop across the electrodes. In the whole range of the discharge conditions we have studied the cathode sheath characteristics are found to obey correctly only to the Child-Langmuir law version with a constant ion mobility. The reason for this phenomenon may be related with a significant conversion of carbon dioxide molecules.

HT6 54 Effects of partially covered metallic wave guide on the linear microwave plasma source with TE-TEM power coupling HAEMARO KIM, MOON-KI HAN, DONG-HYUN KIM, HAE JUNE LEE, HO-JUN LEE, *Pusan Natl Univ* A linear microwave plasma system with TE-TEM power coupling has been used for large scale PECVD processing. In this system, plasma acts as outer conductor of TEM waveguide and microwave power is broadly absorbed around the quartz tube. Due to large power absorption rate, plasma density decreases along the waveguide. For low input power condition, plasma column cannot reach the end of waveguide. Limiting power absorption area by simple partially covered metallic waveguide can improve plasma uniformity and make longer plasma column. When half of the plasma waveguide area is covered by metal in 450 mm long waveguide, local plasma density increases about 20% and density non-uniformity along waveguide decreases from 13% to 7% for pressure 100 mTorr, input power 300W, Ar plasma case.

HT6 55 CAPACITIVELY COUPLED PLASMAS

HT6 56 Radial Distribution of Plasma Parameters in an Asymmetric Coaxial Capacitive Discharge* JEREMY PESHL, MILKA NIKOLIC, JANARDAN UPADHYAY, SVETOZAR POPOVIC, LEPSHA VUSKOVIC, *Old Dominion University* It has been shown that plasma processing is a promising technique for material removal from the inner surface of superconducting radiofrequency (SRF) cavities used in large particle accelerators. A radiofrequency (rf) Capacitive Coupled Plasma (CCP) is created in a coaxial setup with the powered electrode inside a hollow cylindrical cavity. While a great deal of knowledge has been gathered on effective plasma etching criteria in Ar/Cl_2 discharge such as pressure, temperature, rf power, dc bias voltage, and experiment construction, little is known about important plasma specific parameters. The determination of plasma parameters is important due to the unique cylindrical geometry of the plasma defined by the SRF cavity geometry. This configuration leaves many questions regarding the structure and distribution of the discharge as it relates to radial position. Presented here are the diagnostic methods and subsequent results for both electropositive (Ar) and electronegative (Ar/Cl_2) discharges in a cylindrical coaxial rf CCP. Optical Emission Spectroscopy in conjunction with a robust kinetic model of Argon produces electron temperatures and metastable populations with respect to radial positions of the discharge.

*Supported by DE-SC0014397.

HT6 57 Charged particle dynamics and process control in capacitive RF discharges driven by tailored voltage waveforms in mixtures of Argon and CF_4 STEVEN BRANDT, *Department of Physics, West Virginia University, USA* ZOLTAN DONKO, *Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Hungary* JULIAN SCHULZE, *Institute of Electrical Engineering, Ruhr-University Bochum, Germany; Department of Physics, West Virginia University, USA* The electron power absorption dynamics and the Electrical Asymmetry Effect (EAE) are computationally investigated for Argon-CF_4 gas mixtures in geometrically symmetric capacitively coupled plasmas. Simulations are performed for both single- and triple-frequency tailored voltage waveforms at 20 and 60 Pa, using a fundamental frequency of 13.56 MHz and its consecutive harmonics. The results at 60 Pa show electron power absorption mode transitions between the Drift-Ambipolar (DA) mode and the α-mode induced by varying the admixture of Ar to CF_4, which leads to a change of the plasma chemistry. In the triple-frequency cases small argon admixtures (of the order of 10%) strongly affect the electron power absorption dynamics and the symmetry of the discharge. The change of the electrical generation of a DC self-bias via the EAE, the ion flux-energy distribution functions of different ion species at the electrodes, and the excitation of resonance effects are studied as a function of the mixing ratio of these two gases. The results are expected to be highly relevant for plasma processing, where such gas mixtures are often used.

HT6 58 PIC/MCC simulation for magnetized capacitively coupled plasmas driven by combined dc/rf sources* SHALI YANG, YA ZHANG, WEI JIANG, *Huazhong University of Science and Technology, School of Physics, Wuhan, Hubei, CN* HONGYU WANG, *Anshan Normal University, School of Physics Science and Technology, Anshan, CN* SHUAI WANG, *Northeastern University, School of Physics, Shenyang, Liaoning, CN* Hybrid dc/rf capacitively coupled plasma (CCP) sources have been popular in substrate etching due to their simplicity in the device structure and better plasma property. In this work, the characteristics of magnetized capacitively coupled plasmas driven by combined dc/rf sources are described by a one-dimensional Particle-in-cell/Monte Carlo collision (PIC/MCC) model. The simulation is using a rf source of

13.56MHz in argon and at a low pressure of 50mTorr. The effects of dc voltage and magnetic field on the plasmas are examined for 200–400V and 0–200Gs. It is found that, to some extent, dc voltage will increase the plasma density, but plasma density drops with increasing dc voltage. The magnetic field will enhance the plasma density significantly, due to the magnetic field will increase the electron life time and decrease the loss to the electrodes. In the bulk plasma, electron temperature is increased with the magnetic field but decreased with the dc voltage. The electron temperature in sheath is higher than in bulk plasma, due to stochastic heating in sheath is greater than Ohmic heating in bulk plasma under low gas pressure.

*National Natural Science Foundation of China (11405067, 11105057, 11305032, 11275039).

HT6 59 Frequency dependence of the Electrical Asymmetry Effect in electronegative capacitive RF discharges driven by Tailored Voltage Waveforms JULIAN SCHULZE, *Department of Physics, West Virginia University, Institute for Electrical Engineering, Ruhr-University Bochum* EDMUND SCHUENGEL, *Department of Physics, West Virginia University* BASTIEN BRUNEAU, ERIC JOHNSON, JEAN-PAUL BOOTH, *Ecole Polytechnique* ARANKA DERZSI, ZOLTAN DONKO, *Hungarian Academy of Sciences* DEBORAH O'CONNELL, TIMO GANS, *York Plasma Institute* Capacitively coupled RF plasmas operated in CF_4 at 80 Pa and driven by voltage waveforms composed of four consecutive harmonics are investigated for different fundamental driving frequencies (2.86 - 13.56 MHz) using PIC/MCC simulations and an analytical model. In contrast to previous findings in electropositive discharges the absolute value of the DC self-bias generated via the Electrical Asymmetry Effect for peak waveforms is found to increase as the fundamental frequency is reduced, providing an increased range over which it can be tuned by phase control. The analytical model reveals that this increased DC self-bias is caused by changes in the spatial profile and the mean value of the net charge density in the grounded electrode sheath induced by varying the fundamental driving frequency for peak waveforms. The spatio-temporally resolved simulation data show that as the frequency is reduced the grounded electrode sheath region becomes electronegative. This strongly affects the electron power absorption dynamics and the discharge symmetry.

HT6 60 Spatial structure of plasma density and electron temperature in capacitive RF discharges with a single ring-shaped narrow trench of various depths JULIAN SCHULZE, *Department of Physics, West Virginia University, Institute for Electrical Engineering, Ruhr-University Bochum* EDMUND SCHUENGEL, *Department of Physics, West Virginia University* NAOKI MATSUMOTO, YASUNORI OHTSU, *Saga University* Capacitive RF plasmas are used for a variety of technological applications, but suffer from low plasma densities and poor lateral uniformity. This limits the system throughput. Here, the effect of implementing a single narrow trench of 2 mm width and various depths (5 – 15 mm) into the powered electrode on the spatial structure of the electron density and temperature is studied experimentally by probe measurements. The plasma is driven at 13.56 MHz in Argon at a fixed pressure (~50 Pa) and power (20 W). The plasma density is found to increase in the presence of the trench and its radial profile shows a peak above the trench. The density becomes homogeneous further away from the electrode at all trench depths and the electron temperature distribution remains uniform. The measured radial density profiles are in good agreement with a diffusion model for all trench depths. Under the conditions investigated the trench of 10 mm depth is found to result in the highest density at various axial and radial positions. The results show that the radial uniformity of the plasma density at various axial positions can be improved by using structured electrodes of distinct depths.

HT6 61 INDUCTIVELY COUPLED PLASMAS

HT6 62 Effect of Electron Energy Distribution on the Hysteresis of Plasma Discharge: Theory, Experiment, and Modeling* HYO-CHANG LEE,† *Korea Research Institute of Standards and Science (KRISS)* CHIN-WOOK CHUNG, *Hanyang University* Hysteresis, which is the history dependence of physical systems, indicates that there are more-than-two stable points in a given condition, and it has been considered to one of the most important topics in fundamental physics. Recently, the hysteresis of plasma has become a focus of research because stable plasma operation is very important for fusion reactors, bio-medical plasmas, and industrial plasmas for nano-device fabrication process. Interestingly, the bi-stability characteristics of plasma with a huge hysteresis loop have been observed in inductive discharge plasmas Because hysteresis study in such plasmas can provide a universal understanding of plasma physics, many researchers have attempted experimental and theoretical studies. Despite long plasma research, how this plasma hysteresis occurs remains an unresolved question in plasma physics. Here, we report theory, experiment, and modeling of the hysteresis [1]. It was found experimentally and theoretically that evolution of the electron energy distribution (EED) makes a strong plasma hysteresis. In Ramsauer and non-Ramsauer gas experiments, it was revealed that the plasma hysteresis is observed only at high pressure Ramsauer gas where the EED deviates considerably from a Maxwellian shape. This hysteresis was presented in the plasma balance model where the EED is considered. Because electrons in plasmas are usually not in a thermal equilibrium, this EED-effect can be regarded as a universal phenomenon in plasma physics.

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HT6 63 Coupling mechanisms in inductive discharges with RF substrate bias driven at consecutive harmonics with adjustable relative phase THOMAS STEINBERGER, *Department of Physics, West Virginia University, Morgantown, USA* BIRK BERGER, JULIAN SCHULZE, *Department of Physics, West Virginia University, Morgantown, USA; Institute for Electrical Engineering, Ruhr-University Bochum, Germany* EDMUND SCHUENGEL, MARK KOEPKE, *Department of Physics, West Virginia University, Morgantown, USA* Hybrid combinations of inductive and capacitive RF discharges are commonly used for plasma etching because the inductive coupling ensures a high plasma density, while the capacitive coupling allows the control of the ion bombardment energy at the substrate. We experimentally study the coupling mechanisms between the two driving-voltage sources in such a plasma driven inductively at 13.56 MHz and capacitively at 27.12 MHz in argon and neon at low pressure. We find that the resulting DC self-bias can be controlled via the Electrical Asymmetry Effect by adjusting the relative phase between the two driving harmonics in the E-mode. Langmuir probe measurements and Phase Resolved Optical Emission Spectroscopy (PROES) reveal that the addition of the applied RF-bias in the plasma acts as a catalyst for the transition between E- and H-mode. PROES measurements generally show that the electron power absorption dynamics are affected by the relative phase between the two driving voltage waveforms and by the ratio of the inductive to the capacitive driving powers. Finally, the ion flux-energy distribution function is measured at the RF-powered electrode and found also to be affected by coupling effects.

HT6 64 Effects of hydrogen as sheath gas on properties of inductive coupled thermal plasma for B_4C/Cu functionally gradient material preparation QIJIA GUO, PENG ZHAO, LIN LI, GUOHUA NI, XIAODONG ZHANG, *Institute of Plasma Physics, Chinese Academy of Sciences, PO Box 1126, Hefei 230031, China* INSTITUTE OF PLASMA PHYSICS, CHINESE ACADEMY OF SCIENCES, PO BOX 1126, HEFEI 230031, CHINA TEAM B_4C/Cu functionally gradient material (FGM) is a promising candidate for plasma facing material (PFM) in fusion device. Thermal Plasma spraying technology is supposed to be suitable for the B_4C/Cu FGM preparation. In this work, inductively coupled thermal plasma (ICTP) is used to prepare the B_4C/Cu FGM. However, the high gas temperature of pure Ar plasma can damage the torch and it's thermal conductivity is low. The hydrogen has high thermal conductivity, so the mixture gas of Ar and hydrogen is used as sheath gas to protect the ICP torch and enhance the thermal conductivity of the plasma. Optical emission spectroscopy is used to diagnose the properties of ICTP to determine the optimum condition for preparation process. In addition, to control the preparation process, some atomic emission lines and prepared material changed with experiment conditions will be studied. All the plasma properties would give us an insight on the mechanism and the possibility of improving the process.

HT6 65 Electron heating in the inductive discharge array (IDA): theoretical concept and first measurements PHILIPP AHR, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum* Besides the common stochastic heating effect in inductively coupled plasmas, recently a novel heating mechanism was identified theoretically by Czarnetzki and Tarnev [1]. It considers the movement of electrons in a plane parallel to the induced electric field lines, in contrast to the well-known case, when the considered electrons move perpendicular. To enable the possibility of non-local energy gain for electron in this parallel plane, a periodically structured electric field was proposed. To experimentally verify this hypothesis a new plasma source was designed and assembled. This source is named Inductive Discharge Array (IDA). The special spatial field structure is realized by a large electrode with an array of 6 x 6 small plane inductive coils. Due to the use of two separate electric circuits, both electric field structures mentioned in [1] can be achieved. Here the theoretical background and the relevant design considerations are presented. In addition first experimental results are shown.

[1]U. Czarnetzki and Kh. Tarnev, Phys. Plasmas **21**, 123508 (2014).

HT6 66 MAGNETICALLY ENHANCED PLASMAS: ECR, HELICON, MAGNETRON, OTHERS

HT6 67 Generation of off-axially localized tail electrons in helical antenna produce cylindrical plasma SONU YADAV, SOUMEN GHOSH, SAYAK BOSE, P K CHATTOPADHYAY, J GHOSH, D BORA, *Institute for Plasma Research* Off-axially localized tail electrons are observed in helical antenna produce cylindrical radio frequency (RF) plasma. Although, tail electrons are commonly observed in capacitive and inductive plasmas, localization of their population only at the off-axis of a cylindrical RF system is very unique. Moreover, we are reporting the generation of tail electrons even in absence of double layer in expanding helical antenna produce plasma. It is also shown that the confinements of these tail electrons are restricted only at the off-axis at Argon fill pressure bellow $1x10^{-3}$mbar. Experimental results will be presented to show that the tail electrons which generate off-axially in the source chamber are also found at the expansion chamber. External axial diverging magnetic field lines are bringing them from narrow source to large expansion chamber. To understand the underline mechanism of these tail electrons generation, role of (a) RF electric fields via changing RF source power and (b) their off-axial confinement with rising magnetic fields are discussed. Quantitative discussion on self-consistent model for collisionless RF power coupling with edge electrons will also be presented.

HT6 68 Plasma Parameters Characterization of Large Diameter Inverted Cylindrical Magnetron Discharge RAMKRISHNA RANE, SUBRATO MUKHERJEE, *Institute for Plasma Research* In this study, magnetically enhanced large cathode diameter inverted magnetron discharge is characterized for its plasma properties. The current-voltage characteristics at different operating pressure and magnetic field is studied and compared with post cathode configuration. The radial profile of plasma potential, floating potential, plasma density, electron temperature is measured by emissive probe, double langmuir probe etc. The effect of magnetic field on the plasma properties is studied for different operating pressure and discharge voltages. The higher anode fall is observed in case of inverted magnetron for lower operating pressure. It is also found that at very low operating pressure and higher magnetic field, the discharge is transformed to high impedance low current discharge confined near the anode. The oscillations in floating potential are also studied when the discharge is operating in this low current mode.

HT6 69 Time resolved ion energy distribution functions of non-reactive and reactive high power impulse magnetron sputtering of titanium KATHARINA GROSSE, WOLFGANG BREILMANN, CHRISTIAN MASZL, JAN BENEDIKT, ACHIM VON KEUDELL, *Ruhr-University Bochum* High power impulse magnetron sputtering (HiPIMS) is a technique for thin film deposition and can be operated in reactive and non-reactive mode. The growth rate of HiPIMS in non-reactive mode reduces to 30% compared to direct current magnetron sputtering (dcMS) at same average power. However, the quality of the coatings produced with HiPIMS is excellent which makes these plasmas highly appealing. In reactive mode target poisoning is occurring which changes the plasma dynamics. An advantage of reactive HiPIMS is that it can be operated hysteresis-free which can result in a higher growth rate compared to dcMS. In this work thin films are deposited by a HiPIMS plasma which is generated by short pulses of 100 μs with high power densities in the range of 1 kW/cm^2. Ar and Ar/N_2 admixtures are used as a working gas to sputter a 2" titanium target. The particle transport is analysed with time resolved ion energy distribution functions which are measured by a mass spectrometer with a temporal resolution of 2 μs. Phase resolved optical emission spectroscopy is executed to investigate the particle dynamics of different species. The time and energy resolved particle fluxes in non-reactive and reactive mode are compared and implications on the sputter process are discussed.

HT6 70 HIGH PRESSURE DISCHARGES: DIELECTRIC BARRIER, DISCHARGES, CORONAS, BREAKDOWN, SPARKS

HT6 71 Fast optical and electrical diagnostics of pulsed spark discharges in different gap geometries* HANS HÖFT, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* TOM HUISKAMP, *Eindhoven University of Technology, Dept. of Electr. Engineering, P.O. Box 513, 5600 MB Eindhoven, The Netherlands* MANFRED KETTLITZ, *INP Greifswald* Spark discharges in different electrode configurations and with various electrode materials were ignited in air at atmospheric pressure using a custom build pulse charger with $\approx 1\ \mu s$ voltage rise time (up to 28 kV) in single shot operation. Fast voltage and current measurements were combined with iCCD imaging with high spatial resolution (better than 10 μm) on pin-to-pin, pin-to-half-sphere and symmetrical half-sphere tungsten electrodes and symmetrical half-sphere brass electrodes for electrode gaps of 0.1 to 0.7 mm. Breakdown voltages, consumed electrical energies and the discharge emission structures as well as the discharge diameters were obtained. Because of the synchronization of the electrical measurements and the iCCD imaging (i.e. one complete data set for every shot), it was possible to estimate the current density and the change of the discharge pattern, such as single or multiple channels, for all cases.

*EU funding under Grant No 316216 (PlasmaShape).

HT6 72 Self-organized plasmas formed by accumulated charge in dielectric barrier discharge HARUAKI AKASHI, TOMOKAZU YOSHINAGA, *National Defense Academy* Atmospheric pressure dielectric barrier discharges (DBDs) have been widely applied to various research fields, such as bio-medical treatment, toxic decomposition and so on. However, the details of DBD have not been understood yet. Because the phenomena occur in nanosecond time scale under atmospheric pressure. It is known that DBDs are significantly affected by accumulated charges on dielectrics, but the distributions and development of accumulated charges are not known for years. To clarify the distributions and the developments of accumulated charges on dielectrics and electron behavior in the vicinity of dielectrics, DBDs in atmospheric pressure oxygen have been simulated using a two dimensional fluid model with relatively high electron emission coefficient. In this condition, DBD simulation results are obtained in so called self-organized form. As a result, the locations of highly accumulated charges are at where the primary streamers reached in a half cycle. And the charges on the dielectrics become almost zero by the electrons after the change of discharge voltage polarity. The electron distribution in the vicinity of the dielectric forms similar to that of accumulated charges to compensate the charges. Excess electrons in front of dielectric become the seed electrons for next half cycle. This continuation makes discharge in self-organized form.

HT6 73 The effect of humidity on ionic wind velocity in ambient air* SHE CHEN, J.C.P.Y. NOBELEN, S. NIJDAM, *Eindhoven University of Technology* Due to the evolution of portable electronics and LED lightning system, advances in air cooling technologies must also keep pace. Active cooling by ionic wind, which is usually generated by corona discharge, can greatly reduce the noise and lifetime issues compared to the mechanical fans. The wind is induced when a gas discharge is formed, and neutral molecules gain their energy by the momentum transfer of ion-neutral collisions. However, there is few discussion about the effect of gas composition such as humidity on the wind generation and the physical mechanism is not clear. In the experiment, a positive 5-20 kV DC voltage is applied to the needle-cylinder electrodes with separation of 20 mm. The ionic wind velocity is measured by hot wire anemometry. As the relative humidity (RH) in the ambient air increases, the velocity is found to be severely inhibited. The current is also measured between the cylinder electrode and earth. The results show that the DC component of corona current decreases when RH increases. Since both the discharge current and the ion mobility are reduced when RH increases, their combined effects determine the ionic wind velocity.

*This work is supported by STW project 13651.

HT6 74 Multiple surface DBD electrode system for efficient and controlled generation of ozone* VACLAV PRUKNER, PETR HOFFER, MILAN SIMEK, *Institute of Plasma Physics of the CAS Prague* Electrical characteristics and ozone production measurements were performed to evaluate the efficiency of ozone generation using an amplitude-modulated AC Surface Dielectric Barrier Discharge (SDBD) in dry synthetic air and pure oxygen at atmospheric pressure. To increase the concentration and production of ozone we used the multiple SDBD electrode system consisting of several identical elements in parallel configuration. Each SDBD element is made of a thin alumina plate (10cm x 10 cm x 0,065cm) with metallic strips deposited on the upper side as a HV electrode and full square or strips on the opposite side as a ground electrode. An influence of a photocatalyst on ozone production was studied as well by inserting thin alumina plates coated with titanium dioxide thin films between SDBD electrodes. Alternatively, the SDBD electrodes directly coated with titanium dioxide were tested either. Dependence of ozone production on the discharge duty cycle and gas flow rate of 0,8 slm – 10 slm were evaluated.

*Work supported by TACR (Contract No. TA03010098).

HT6 75 Investigation of the Time Evolution and Species Production in a 2-Dimensional Packed Bed Reactor* KENNETH ENGELING, JULIUSZ KRUSZELNICKI, MARK KUSHNER, JOHN FOSTER, *University of Michigan* Plasma production in microporous media has potential to enable a number of technologies ranging from flameless combustion to environmental hazard mitigation addressing air borne pollutants. Packed bed reactors (PBRs) is one such technology that relies on plasma production in microporous media. The physics of plasma production and transport in such media however remains poorly understood. In order to better understand the plasma propagation and plasma driven chemical reaction within microporous media, absorption spectroscopy and time-resolved imaging diagnostics are being utilized. We report on plasma driven species formation and plasma discharge spatial structure and evolution characteristics found in the 2-dimensional representation of a PBR.

*Work supported by US DOE Office of Fusion Energy Science and the National Science Foundation.

HT6 76 Effects of pulse-to-pulse residual species on discharges in repetitively pulsed discharges through packed bed reactors* JULIUSZ KRUSZELNICKI, KENNETH W. ENGELING, JOHN E. FOSTER, MARK J. KUSHNER, *University of Michigan* Atmospheric pressure dielectric barrier discharges (DBDs) sustained in packed bed reactors (PBRs) are being investigated for conversion of toxic and waste gases, and CO_2 removal. These discharges are repetitively pulsed having varying flow rates and internal geometries, which results in species from the prior pulse still being in the discharge zone at the time the following discharge pulse occurs. A non-negligible residual plasma density remains, which effectively acts as preionization. This residual charge changes the discharge properties of subsequent pulses, and may impact important PBR properties such as chemical selectivity. Similarly, the residual neutral reactive species produced during earlier pulses will impact the reaction rates on subsequent pulses. We report on results of a computational investigation of a 2D PBR using the plasma hydrodynamics simulator *nonPDPSIM*. Results will be discussed for air flowing though an array of dielectric rods at atmospheric pressure. The effects of inter-pulse residual species on PBR discharges will be quantified. Means of controlling the presence of residual species in the reactor through gas flow rate, pulse repetition, pulse width and geometry will be described. Comparisons will be made to experiments.

*Work supported by US DOE Office of Fusion Energy Science and the National Science Foundation.

HT6 77 Effects of oxygen concentration on atmospheric pressure dielectric barrier discharge in Argon-Oxygen Mixture* XUECHUN LI, DIAN LI, YOUNIAN WANG, *Dalian University of Technology* A dielectric barrier discharge (DBD) can generate a low-temperature plasma easily at atmospheric pressure and has been investigated for applications in trials in cancer therapy, sterilization, air pollution control, etc. It has been confirmed that reactive oxygen species (ROS) play a key role in the processes. In this work, we use a fluid model to simulate the plasma characteristics for DBD in argon-oxygen mixture. The effects of oxygen concentration on the plasma characteristics have been discussed. The evolution mechanism of ROS has been systematically analyzed. It was found that the ground state oxygen atoms and oxygen molecular ions are the dominated oxygen species under the considered oxygen concentrations. With the oxygen concentration increasing, the densities of electrons, argon atomic ions, resonance state argon atoms, metastable state argon atoms and excited state argon atoms all show a trend of decline. The oxygen molecular ions density is high and little influenced by the oxygen concentration. Ground state oxygen atoms density tends to increase before falling. The ozone density increases significantly. Increasing the oxygen concentration, the discharge mode begins to change gradually from the glow discharge mode to Townsend discharge mode.

*Project supported by the National Natural Science Foundation of China (Grant No. 11175034).

HT6 78 Spatial profiles of the cathode layer parameters in the strongly constricted and diffuse atmospheric pressure glow discharges LEANID SIMONCHIK, VALERY ARKHIPENKO, ALIAKSANDRA KAZAK, *Institute of physics of NAS of Belarus* In high-current atmospheric pressure glow discharges without limiting walls of discharge chamber, the degree of positive column contraction should be determined by the relation of its diameter to the dimension of negative glow which are defined by transverse electron concentration or light emission profiles. In this report, it is shown experimentally that parameters of the cathode fall in normal atmospheric pressure glow discharge with diffuse positive column more or less fit the scaling laws. Radially limited heat flow from the strongly constricted positive column to the cathode results in inhomogeneous distribution of the reduced electric field along the cathode surface. At that, the reduced electric field decreases radially and the cathode fall parameters mismatch the scaling laws at the center of the cathode fall. It is established that the cathode heating resulting from the discharge current flow leads in such a discharge to the increase in the cathode fall. On the contrary, additional heating of cathode by external heat source decreases the cathode fall. The gas heating at the edge of cathode fall happens mainly due to both the heat transfer from hot cathode and the current flow. Spatial profiles of current flow lines in cathode region are discussed.

HT6 79 1D fluid model of the dielectric barrier discharge in chlorine SVETLANA AVTAEVA, *Novosibirsk State University* The 1D fluid model of the dielectric barrier discharge (DBD) in pure chlorine is developed. The discharge is excited in 8 mm gas gap between quartz dielectric layers of 2 mm thickness covered metallic electrodes. The source voltage $U_S = U_0 \sin\omega t$ with a frequency 100 kHz and amplitude 8 kV is applied to the electrodes. Chlorine pressure is varied from 15 to 100 Torr. At pressure of 15 Torr a breakdown appears with voltage drop across the discharge gap about 1 kV whereas at 100 Torr it appears with voltage drop about 2 kV. After the first current spike some lower current spikes are observes with chlorine pressure of 100 Torr and large in number current spikes of about identical magnitude are observed with the pressure of 15 Torr. The maximal current density at all pressures reaches about 4 mA/cm^2 Total density of surface charge deposited on the electrodes during a half-cycle decreases with chlorine pressure because duration of the current spike discharge phase reduces with chlorine pressure. The average power density inputted in the discharge is 2.5-5.8 W/cm^3 per a cycle. The Cl_2 plasma is electronegative, the most abundant ions are Cl_2^+ and Cl^-. It is shown, that ions get about 95% of the discharge power as electrons get about 5% of the discharge power. 67-97% of the electron power is spending for dissociation and ionization of Cl_2 molecules. Emission of Cl^* atoms and Cl_2^* molecules is weak.

HT6 80 MICRODISCHARGES: DC, RF, MICROWAVE

HT6 81 Investigation of atmospheric pressure glow microdischarge between flat cathode and needle anode in helium and argon* ALEXANDER ASTAFIEV, VLADIMIR BELYAEV, ROMAN ZAMCHII, ANATOLY KUDRYAVTSEV, OLGA STEPANOVA, *Saint Petersburg State University, St. Petersburg, Russia* ZHAOQUAN CHEN, *Anhui University of Science and Technology, Huainan, China* DC atmospheric-pressure glow microdischarge was generated between a flat cathode and needle anode with a diameter of 100 μm in a special chamber with helium or argon. Dependences of discharge parameters on an interelectrode gap was investigated with an original experimental setup based on a movable arm on the hinge joint which allowed changing the gap with a step of 5 μm. The gap was varied from 5 to 700 μm. Discharge current was 1-21 mA. Such discharge cell has a very low interelectrode capacitance and provides increasing the stability of the discharge against arc formation (transition to RC oscillations mode) at low currents of 1 mA. A weak dependence of discharge voltage across the gap was revealed in helium at 100-250 μm between the electrodes (normal discharge). In contrast to this, glow microdischarge in argon has a descending current-voltage characteristic and unstable nature. The discharge voltage depending on the gap changes significantly slower than in helium. According to our estimations, the strength of electrical field of positive glow in argon is 5 times lower than in helium.

*Saint Petersburg State University (Grant No. 0.37.218.2016).

HT6 82 Metastable densities in rf-driven atmospheric pressure microplasma jets in argon and helium MARC BOEKE, STEFAN

SPIEKERMEIER, JOERG WINTER, *Ruhr-Universitaet Bochum* Rf-driven atmospheric pressure microplasma jets (μ-APPJ) are usually operated in the homogeneous glow mode (α-mode). At higher powers the glow discharge becomes unstable due to thermal instabilities and turns into a constricted γ-like discharge (constricted mode), which can damage the jet due to the significantly increased temperature in this operation mode. To prevent these instabilities, rf-driven μ-APPJs are predominantly operated in helium since it provides a better thermal conductivity than argon. However, since argon is much more cost-effective, it is worthwhile to achieve a stable operation of the μ-APPJ using argon as feed gas. Metastable atoms play an important role in the stability of atmospheric pressure discharges, since they pose an important source of electrons via stepwise ionization and penning ionization. To understand the basic processes that lead to the transition from α- to the constricted mode, helium and argon metastable densities have been determined in the μ-APPJ in different operation modes using tunable diode laser absorption spectroscopy (TDLAS). Supported by DFG within (FOR1123).

HT6 83 OH rotational temperature measurements via a two temperature distribution analysis in plasma with water microdroplets MASANAO TSUMAKI, TSUYOHITO ITO, *Osaka University* We study plasma processing with water/solution microdroplets for a new nanoparticle synthesis method. In the process, it is important to know gas temperature (Tg) for understanding the mechanism of the particle growth and controlling its properties. Since OH emissions are naturally observed in such plasma, the rotational temperature (Tr) of OH (A-X) is estimated and compared with Tr from N_2 (C-B). The plasma is generated by dielectric barrier discharges in He with N_2 (2.6%) gas flow, and microdroplets are generated by an ultrasonic atomizer and carried into He/N_2 plasma. Optical emission spectroscopy revealed that with the increase of voltage and frequency of plasma generation, the Tr of N_2 increases. While the good theoretical spectrum fit on N_2 experimental spectrum could be achieved, it was hard to obtain a reasonable fit for the OH spectrum with a single rotational energy distribution. On the other hand, two rotational distribution analysis could reproduce the experimental spectrum of OH and the lower Tr agrees to Tr by N_2. The results suggest that the lower Tr obtained with the two rotational temperature analysis of OH spectrum represents Tg of the environment.

HT6 84 Reactive Microplasma Discharge for In-Situ Study of Surface Modification* SOPHIA GERSHMAN, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* In-situ evaluation of surface modifications induced by reactive plasma-surface interactions is an important part of the fundamental studies of the processes at plasma-surface interfaces. We have developed a microdischarge cell for use inside an Environmental Scanning Electron Microscope (ESEM). Plasma is ignited inside hollow cylindrical electrode and interacts with ta grounded substrate. The substrate is interchangeable and the plasma gasses CO_2, N_2, water vapor, are consistent with the requirements of the ESEM. The microdischarge cell has been characterized at 2-8 torr and tested in an ESEM in a hollow cathode (MHC) or a hollow anode (MHA) configuration. The electrical measurements show that the MHC configuration has lower reduced field and higher plasma density than MHA. The optical emission spectra of the CO and N_2 bands and H lines were used to find the rotational temperature of 450 K in both configurations, and the vibrational temperature of 3700 K for the MHC and 4500 K for the MHA. The electron excitation temperature is higher in the MHA configuration. MHA can potentially offer a better controllability of the electron energy distribution function, which is useful for micro plasma applications.

*This work was supported by the US Airforce.

HT6 85 Interaction between a microplasma array and an adjacent dielectric surface* SEBASTIAN DZIKOWSKI, VOLKER SCHULZ-VON DER GATHEN, *Ruhr-Universitaet Bochum* Microplasma pixel devices are interesting for applications such as surface modification. A representative is the metal grid array, which is a stable alternative to silicon-based arrays and consists of a dielectric, a grounded electrode and a metal grid with symmetrically arranged cavities. Typically, microplasma arrays are operated close to atmospheric pressure with noble gases like argon and helium. By applying a bipolar triangular voltage waveform with an amplitude of 700 V peak-to-peak and a frequency of 10 kHz to the metal grid, the discharge is ignited in the cavities having a diameter of about 200 and depth of 50 μm. For future applications, such as coating and catalysis, the interaction between the array and a dielectric surface positioned at close distance ($<\sim$200 μm) is of great importance. By application of phase resolved optical emission spectroscopy, the phase dependent expansion of the emission out of the cavities has been observed. Here, we present results of investigations on the dependence of emission structures of the cavities (individually or as group) on pressure, applied voltage and distance between grid and dielectric.

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HT6 86 Net Emission Coefficients for Copper and Iron Plasmas FRANK KASSUBEK, *ABB Corporate Research, Baden-Dättwil, Switzerland* ODED ZILBERBERG, *ABB Corporate Research, Baden-Dättwil, Switzerland; ETH Zürich, Institute for Theoretical Physics* CHARLES DOIRON, *ABB Corporate Research, Baden-Dättwil, Switzerland* Radiative heat transfer is an important mechanism for heat transport in electrical arcs, e.g. in electrical switchgear. An exact description of this phenomenon is important (i) for the energy balance of the arc itself, and (ii) for the estimate of the escaping radiation that leads to evaporation of polymer nozzles; the evaporated material and its flow have a strong effect on the arcs. For low voltage arcs, the plasma composition within the arc is dominated by the contact material. In the present study, we compare copper and iron. Especially, we discuss the calculation of absorption and emission spectra and their characterisation by net emission coefficients. The latter describe well the effective power balance at the centre of the arc. We show that in addition to the net emission coefficients, it is important to characterise the radiation that is emitted from the arc core.

HT6 87 THERMAL PLASMAS: ARCS, JETS, SWITCHES, OTHERS

HT6 88 Characterization, mechanical, and corrosion properties of chromium carbide films by using a 90° bend magnetic filtered cathodic vacuum arc (FCVA) method CHIH-CHIANG WANG, CHUN-CHUN LIN, YA-CHYI CHEN, FUH-SHENG SHIEU, *National Chung Hsing University* HAN C. SHIH, *Chinese Culture University* The 90° bend magnetic FCVA that equipped with the target of Cr (99.95%) and C_2H_2/Ar gas mixture deposited a high quality of chromium carbide films on the AISI D2 steel and Si wafer. The FCVA has been employed to eliminate the macroparticles during the film deposition. Various deposition temperatures of ambient temperature, 300, and 500° and negative substrate bias voltages ranging from −50 to −550V were applied. The microstructure of chromium carbide films was investigated by GIXRD and HRTEM. The atomic concentrations of C and Cr were measured by AES. The chemical bonding was elucidated by XPS, showing that the total C-Cr bond contents increased with increasing deposition temperature. As the substrate bias voltage increased from −50 to −550V, the phase transformed from amorphous to crystalline Cr_3C_2. The mechanical properties were evaluated by nanoindetation, nanoscratch, and scratch test. The surface roughness decreased from 2.05 to 0.34nm and the friction coefficient decreased from 0.28(amorphous) to 0.22(crystalline) as the substrate bias voltage increased from −50 to −550V. The corrosion resistance showed that the Cr_3C_2 coated steel had the noticeable increasing with the negative bias voltage up to −550V, and the pitting corrosion did not appear on the Cr_3C_2 coated steel.

HT6 89 Arc Conductance and Flow Velocity Affected by Transient Recovery Voltage REO FUKUOKA, YUYA ISHIKAWA, SEISUI ONO, KEN SATO, SHINJI YAMAMOTO, TORU IWAO, *Tokyo City University, Setagaya, Tokyo 158-8557, JAPAN* Recently, the stable supply of electric power is indispensable. The GCB (Gas Circuit Breaker) can prevent the spread of the fault current. However, it should have the reliability more. Therefore the GCB has been researched for performance improvement of the arc interruption of abnormal fault current without the fail. Therefore, it is important to prevent the breakdown such as the re-ignition and thermal re-ignition of arc after the arc interruption. It is necessary to reduce the arc conductance in order to prevent the re-ignition of arc. The arc conductance is derived from the temperature distribution and the volume of the arc. The temperature distribution of the arc is formed by convection. In this research, the arc conductance and flow velocity affected by transient recovery voltage are elucidated. The flow rate and temperature distribution of the arc is calculated with changing transient recovery voltage. In addition, the arc conductance is calculated in order to know the extinguish arc ability. As a result, when the transient recovery voltage increases, the probability of re-ignition increases. Therefore, the arc temperature and the arc conductance were increased.

HT6 90 Distribution of Argon Arc Contaminated with Nitrogen as Function of Frequency in Pulsed TIG Welding HIROKI TAKAHASHI, TATSURO TANAKA, SHINJI YAMAMOTO, TORU IWAO, *Tokyo City University, Setagaya, Tokyo 158-8557, JAPAN* TIG arc welding is the high-quality and much applicable material joining technology. However, the current has to be small because the cathode melting should be prevented. In this case, the heat input to the welding pool becomes low, then, the welding defect sometimes occurs. The pulsed TIG arc welding is used to improve this disadvantage This welding can be controlled by some current parameters such as frequency However, few report has reported the distribution of argon arc contaminated with nitrogen It is important to prevent the contamination of nitrogen because the melting depth increases in order to prevent the welding defects. In this paper, the distribution of argon arc contaminated as function of frequency with nitrogen in pulsed TIG welding is elucidated. The nitrogen concentration, the radial flow velocity, the arc temperature were calculated using the EMTF simulation when the time reached at the base current. As a result, the nitrogen concentration into the arc became low with increasing the frequency The diffusion coefficient decreased because of the decrement of temperature over 4000 K. In this case, the nitrogen concentration became low near the anode. Therefore, the nitrogen concentration became low because the frequency is high.

HT6 91 Study of transfer efficiency in a screw pinch plasma ALEXANDER PUTH, THILO ACKERMANN, MARCUS IBERLER, JOACHIM JACOBY, DOMINIC MANN, GE XU, *IAP, Goethe-University Frankfurt am Main* A screwpinch for UV generation and possible FAIR plasma stripper applications was designed based on a previous development. The intention was to increase the applicable voltage and as a result the electron density. Research was conducted into the transfer efficiency for plasma generation providing preliminary values up to 66%. The device operates at a frequency of approximate 14 kHz and is characterised by a capacity of 34 μF, a thyratron switch with a maximum current rise time of 5 MA/μs as well as a variable set of up to 5 planar coils with diameters of 172 and 208 mm. A cylindrical volume of 4 l can thusly be ignited within the region of $5 \cdot 10^{-3}$ to 1 mbar with an applied voltage of 6 to 13 kV, resulting in peak electron densities of $4 \cdot 10^{16}$ electrons per cm^3.

HT6 92 Removal of Oxide Layer Using Vacuum Arc Cathode Spot with Transverse External Magnetic Field SHIKO KANEDA, ARISA TAKAHASHI, SHINJI YMAMOTO, TORU IWAO, *Tokyo City University, Setagaya, Tokyo 158-8557, Japan* A remarkable characteristic of a cathode spot in a vacuum arc is that the cathode spot moves around the metal at high speed. Cathode spots of vacuum arc have been used for cleaning metal oxide surface. In addition, the adhesion strength increases in the case of thermal spraying because the roughness on the metal surface is formed. However, the removal of oxide layer is not enough and the re-melting occurs because a cathode spot moves with random manner on the metal surface. In this paper, the removal of oxide layer was observed in order to control the cathode spot movement with transverse external magnetic field. Experiment were performed using a SS400 cathode work piece. A high-speed video camera recorded the cathode spot. Then, the obtained images were analyzed by plasma image processing. As a results, the cathode spot moves with retrograde motion under removing the oxide layer when a magnetic field was applied. Then, the moving speed of cathode spot increases with increasing the magnetic field.

HT6 93 Applying a laser-induced incandescence (LII) diagnostic to monitor nanoparticle synthesis in an atmospheric plasma, *in situ** SHURIK YATOM, JAMES MITRANI, *Princeton Plasma Physics Lab* YAO-WEN YEH, MIKHAIL SHNEIDER, *Princeton University* BRENTLEY STRATTON, YEVGENY RAITSES, *Princeton Plasma Physics Lab* A DC arc discharge with a consumed graphite anode is commonly used for synthesis of carbon nanoparticles, including carbon nanotubes (CNTs) and graphene flakes [1-3]. The graphite electrode is physically vaporized by high currents (20-60 A) in a buffer gas at 100-600 torr, leading to nanoparticle synthesis in a low temperature (>1 eV), plasma. Utilizing arc plasma synthesis technique has resulted in the synthesis of higher quality nanomaterials [3]. However, the formation of nanoparticles in arc discharge plasmas is poorly understood. A particularly interesting question is where in the arc the nanoparticles nucleate and grow. In our current work we show the results of studying the formation of carbon nanotubes in an arc discharge, *in situ*, using laser-induced incandescence (LII). The results of LII are discussed in combination with *ex situ* measurements of the synthesized nanoparticles and modeling, to provide an insight into the physics behind nanoparticle synthesis in plasma.

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[1]C. Journet *et al.*, Nature **388**, 756 (1997).
[2]A. J. Fetterman *et al.*, Carbon **46**, 1322 (2008).
[3]M. Keidar *et al.*, Phys. Plasmas **17**, 057101 (2010).

HT6 94 PLASMAS IN LIQUIDS

HT6 95 Pulsed picosecond and nanosecond discharge development in liquids with various dielectric permittivity constants ANDREY STARIKOVSKIY, *Princeton University* The dynamics of pulsed picosecond and nanosecond discharge development in liquid water, ethanol and hexane were investigated experimentally. It is shown that the dynamics of discharge formation fundamentally differ between liquids with low and high dielectric permittivity coefficients. The difference in the nanosecond discharge development in liquid dielectrics may be explained by the formation of micro-discontinuities in the media during the electrostriction compression/rarefaction stage in liquids with high dielectric permittivity. Three possible mechanisms for the propagation of discharge in liquids play a different role depending on the pulse duration. The first is the formation of low density channels in liquid. In the second case the electrostatic forces support the expansion of nanoscale voids behind the front of the ionization wave; in the wave front the extreme electric field provides a strong negative pressure in the dielectric fluid due to the presence of electrostriction forces, forming the initial micro-voids in the continuous medium. Finally, in the third case, when a picosecond electric pulse is utilized, the ionization in the liquid phase occurs as a result of direct electron impact without undergoing a phase transition.

HT6 96 Evolution of Spatial pH Distribution in Aqueous Solution induced by Atmospheric Pressure Plasma SHIGENORI TAKAHASHI, KAKERU MANO, YUI HAYASHI, *Department of Chemical Engineering, Nagoya University* NORIHARU TAKADA, *Nagoya University* HIDEKI KANDA, MOTONOBU GOTO, *Department of Chemical Engineering, Nagoya University* Discharge plasma at gas-liquid interface produces some active species, and then they affect chemical reactions in aqueous solution, where pH of aqueous solution is changed due to redox species. The pH change of aqueous solution is an important factor for chemical reactions. However, spatial pH distribution in a reactor during the discharge has not been clarified yet. Thus, this work focused on spatial pH distribution of aqueous solution when pulsed discharge plasma was generated from a copper electrode in gas phase to aqueous solution in a reactor. Experiments were conducted using positive unipolar pulsed power. The unipolar pulsed voltage at +8.0 kV was applied to the copper electrode and the bottom of the reactor was grounded. The size of the reactor was 80 mm wide, 10 mm deep, and 40 mm high. The electrode was set at distance of 2 mm from the solution surface. Anthocyanins were contained in the aqueous solution as a pH indicator. The change pH solution spread horizontally, and low pH region of 10 mm in depth was formed. After discharge for 10 minutes, the low pH region was diffused toward the bottom of the reactor. After discharge for 60 minutes, the pH of the whole solution decreased.

HT6 97 Emission spectroscopyp of single buble sonoluminescence using argon mixuture water RYOKO YAMADA, MAKOTO MATSUI, SHUN ITO, *Shizuoka Univ* If the liquid has been degassed and is irradiated with a standing acoustic wave, a single bubble sonoluminescence(SBSL) can be generated. It is think that very high temperature and pressure environment is generated inside a SBSL bubble with emission of light. However, little is known about the SBSL emission mechanism. The study is intended as an elucidation of SBSL emission mechanism. In this study, to generate SBSL, the Ar mixture pure water in the 200 ml round bottom flask was irradiated with ultrasound at about 24.1 kHz. SBSL emission of light was detected by PMT. We will acquire the emission spectrum of SBSL using spectroscope and ICCD camera next.

HT6 98 Imaging diagnostics of pulsed plasma discharges in saline generated with various sharp pin powered electrodes L. ASIMAKOULAS, M. L. KARIM, *Centre for Plasma Physics, Queen's University Belfast* L. DOSTAL, F. KRCMA, *Brno University of Technology* W. G. GRAHAM, T. A. FIELD, *Centre for Plasma Physics, Queen's University Belfast* Plasmas formed by 1 ms pulses of between 180 and 300 V applied to sharp pin-like electrodes immersed in saline solution have been imaged with a Photron SA-X2 fast framing camera and an Andor iStar 510 ICCD camera. Stainless steel, Tungsten and Gold electrodes were investigated with tip diameters of 30 μm, 1 μm and < 1 μm respectively. As previously observed, a vapour layer forms around the electrode prior to plasma ignition [1]. For gold and stainless steel lower voltages were required to minimize electrode damage. Preliminary anlaysis indicates at lower voltages for all tips the fast framing results show that light emission is normally centred on a single small volume, which appears to move about, but remains close to the tip. In the case of Tungsten with higher voltages or longer pulses the tip of the needle can heat up to incandescent temperatures. At higher voltages shock wave fronts appear to be observed as the vapour layer collapses at the end of the voltage pulse. Backlighting and no lighting to observe bubble/vapour layer formation and emission due to plasma formation were employed. Sometimes at higher voltages a thicker vapour layer engulfs the tip and no plasma emission/current is observed.

[1]L. Schaper *et al.*, Plasma Sources Sci. Tech. **20**, 034003 (2011).

HT6 99 Investigation Of The High-Voltage Discharge On The Surface Of Gas-Liquid System SHI NGUYEN-KUOK,* ALEKSANDR MORGUNOV,† YURY MALAKHOV,‡ IVAN KOROTKIKH,§ *None* This paper describes an experimental setup for study of physical processes in the high-voltage discharge on the surface of gas-liquid system at atmospheric pressure. Measurements of electrical and optical characteristics of the high-voltage discharge in gas, at the surface of the gas-liquid system and in the electrolyte are obtained. The parameters of the high-voltage discharge and the conditions for its stable operation are presented. Investigations with various electrolytes and cathode assemblies of various materials and sizes were carried out. The installation can be used for the processing and recycling of industrial and chemical liquid waste.

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†Reseacher of Laboratory of Plasma Physics, National Research University MPEI, Krasnokazarmennya Str.14, 111250, Moscow, Russia.
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HT6 100 Volume Mode Excitation In Submerged Bubbles: Towards Reducing Breakdown Voltage For Plasma Generation In Liquids JOSEPH GROELE, JOHN FOSTER, *Univ of Michigan - Ann Arbor* Plasma ignition of submerged gas bubbles reduces the breakdown voltage required to introduce plasma into a liquid. It is possible to further reduce the breakdown voltage of bubbles in liquid water. Local enhancement of the electric field through bubble shape mode activation combined with volume modulation for decreased internal pressure and neutral density is a potential pathway for minimizing breakdown voltage. Although electrohydraulic control of bubble shape has been investigated [1], for the purpose of reducing breakdown voltage, the quantitative benefits of accessing bubble volume modes remain unexplored. Submerged bubble volume modulation may be achieved by sonically or electrohydraulically driving a time-varying sinusoidal field at the Minnaert resonance frequency. Volume mode activation as a possible pathway to reduced breakdown voltage is demonstrated using Rayleigh-Plesset modeling of the transient bubble radius under an applied sinusoidal pressure signal. Results from an experimental investigation aimed at exciting volume modes are also presented. Additionally, results from preliminary experiments aimed at breaking down a volume mode oscillating bubble as a function of internal bubble pressure is presented.

[1]J. Phys. D: Appl. Phys. **45**, 415203 (2012).

HT6 101 Experimental study of low-temperature plasma of electrical discharges with liquid electrodes* VIKTOR ZHELTUKHIN, *Kazan National Research Technological University* ALMAZ GAISIN, *A.N.Tupolev's Kazan National Research Technical University-KAI* Results of the experimental research of discharge between the liquid jet cathode (LJC) and the metal anode are presented. The discharge was studied over the voltage range $U = 100 - 600$ V, discharge current range $I = 0.1 - 0.25$ A, external pressure range $P = 10^5$ Pa, discharge power $P_d = 10 - 150$ W. We used the techniques of infrared thermography and spectral measurements. Schlieren's photography is applied for describing the processes in liquid and gas phase. Results of the experimental researches of discharge current-voltage characteristic (CVC), the surface temperature distribution both on the LJC and the metal anode, a spectral measurements are showed. Effects of action both of breakdown and discharge on the jet flow as well as on the air flow near the discharge are described. It is found that the discharge CVC has an ascending behavior due to increase of plasma current density. The discharge is generated on the borders between the LJC and the metal anode as well as along the LJC misshaping this one. It is established that both the convection streams and an electrolyte drops are formed during the discharge burn. It is found that the discharge temperature in the vicinity of electrode surface reaches $T \approx 348$ K.

*The work was funded by RFBR, according to the research projects No.,14-01-0755.

HT6 102 NEGATIVE ION AND DUST PARTICLE CONTAINING PLASMAS

HT6 103 Synthesis, transport, and retention of tin nanodroplets in a magnetron sputtering source combined with a capacitively-coupled plasma K. SASAKI, K. TAKANARI, *Hokkaido University* The intention of this work was the development of a method for coating metal nanodroplets with thin films having high melting temperatures. To realize this process technology, we combined a magnetron sputtering plasma for synthesizing metal nanoparticles with a capacitively-coupled plasma (CCP) for retaining and heating synthesized nanoparticles. The magnetron sputtering source with a tin target was operated at a high pressure of 400 mTorr. The high pressure induced the condensation of tin atoms in the gas phase, resulting in the formation of tin nanoparticles. The nanoparticles were transported downward, and were trapped in the sheath electric field near the planar electrode for the CCP discharge. The formation, the transport, and the retention of nanoparticles were monitored by laser light scattering. Collected tin nanoparticles did not have agglomerated shapes, suggesting that tin nanoparticles were melted when they were stored in the CCP discharge. The surfaces of tin nanoparticles were oxidized. When we introduced methane before the collection, we observed core-shell nanoparticles without oxidization. Tin nanoparticles were coated with amorphous carbon films by plasma-enhanced chemical vapor deposition of methane.

HT6 104 Dust formation and dynamic in magnetized and non-magnetized microwave discharge KARIM OUARAS, *Laboratoire de Physique des Gaz et des Plasmas, CNRS (UMR8578), Université Paris-Sud, Bât. 210, 91405 Orsay Cedex, France* GUILLAUME LOMBARDI, KHALED HASSOUNI, *LSPM-CNRS Université Paris 13, Sorbonne Paris Cité, F-93490 Villetaneuse, France* Dusty plasmas studies are conducted for several decades to answer to various issues from microelectronic, nanotechnology, astrophysics and thermonuclear fusion devices. These studies are usually conducted in RF discharges at low pressure in which the major physics concerning dust formation mechanisms and dynamic is now well known. In our case, we focus on dust formation and dynamic in (i) microwave plasma under typical pressure conditions of RF discharges (50 Pa) and (ii) in magnetized (ECR: Electron Cyclotron Resonance) microwave plasma under very low pressure condition (0.1 to 1 Pa). The aim of this study is not only for fundamental purpose but also for respond to some issues concerning dust in fusion devices. Thus, we investigate the dust formation mechanisms and dynamic using laser extinction method and laser light scattering imaging coupling with SEM imaging in hydrocarbon plasma and with PVD system with using tungsten target (according to fusion device). We observed that dust formation occurs even if the very low pressure conditions are generally not suitable for nucleation growth in gas phase (the influence of the magnetic field will be discussed). We will also discuss about the particular dust dynamic behavior in microwave discharge in comparison with RF discharge.

HT6 105 Hybrid simulation of nanoparticle growth and transport in a pulsed RF CCP sustained in silane* WEN-ZHU JIA, YUAN-HONG SONG,† YOU-NIAN WANG, *PSEG, Dalian University of Technology* A pulsed RF silane plasma is studied numerically by adopting a self-consistent one-dimensional fluid/MC model. The large anions (typically Si12H25- and Si12H24-) in the discharge are the main precursors in the pathways leading to particle formation in a nucleation process. In order to study detailed growth of nanoparticles, an aerosol general dynamics equation is introduced and self-consistently coupled to the plasma fluid model, in which spatial distribution of nanoparticles, from several to tens of nm in diameter, is investigated. The numerical results show that, the ion drag force on smaller nanoparticles could to some extent exceed the electrostatic force in the plasma bulk, making the nanoparticles generally move towards the plasma boundaries. So the axial spatial distribution of nanoparticles is like a bimodal structure. With increase of the particle size, the distance between two peaks gradually becomes larger, reflecting the appearance of void in the plasma. At the same time, the presence of nanoparticles can lead to a decline of the electron density and a rise of the potential. In addition, by pulsing the RF source, size-controlled nanoparticles are expected to be extracted from the bulk plasma during the afterglow period.

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†Corresponding Author.

HT6 106 Numerical studies from quantum to macroscopic scales of carbon nanoparticules in hydrogen plasma GUILLAUME LOMBARDI, *CNRS LSPM - University Paris 13* ALAIN NGANDJONG, *ITODYS - University Paris Diderot* ZSOLT MEZEI, JONATHAN MOUGENOT, ARMELLE MICHAU, KHALED HASSOUNI, *CNRS LSPM - University Paris 13* MAHAMADOU SEYDOU, FRANÇOIS MAUREL, *ITODYS - University Paris Diderot* Dusty plasmas take part in large scientific domains from Universe Science to nanomaterial synthesis processes. They are often generated by growth from molecular precursor. This growth leads to the formation of larger clusters which induce solid germs nucleation. Particle formed are described by an aerosol dynamic taking into account coagulation, molecular deposition and transport processes. These processes are controlled by the elementary particle. So there is a strong coupling between particle dynamics and plasma discharge equilibrium. This study is focused on the development of a multiscale physic and numeric model of hydrogen plasmas and carbon particles around three essential coupled axes to describe the various physical phenomena: (i) Macro/mesoscopic fluid modeling describing in an auto-coherent way, characteristics of the plasma, molecular clusters and aerosol behavior; (ii) the classic molecular dynamics offering a description to the scale molecular of the chains of chemical reactions and the phenomena of aggregation; (iii) the quantum chemistry to establish the activation barriers of the different processes driving the nanopoarticule formation.

HT6 107 Interaction of UV laser pulses with reactive dusty plasmas FERDI VAN DE WETERING, JOB BECKERS, SANDER NIJDAM, WOUTER OOSTERBEEK, *Eindhoven University of Technology, The Netherlands* EVA KOVACEVIC, JOHANNES BERNDT, *GREMI UMT 7344 CNRS&Universite d'Orleans, France* This contribution deals with the effects of UV photons on the synthesis and transport of nanoparticles in reactive complex plasmas (capacitively coupled RF discharge). First measurements showed that the irradiation of a reactive acetylene-argon plasma with high-energy, ns UV laser pulses (355 nm, 75 mJ pulse energy, repetition frequency 10Hz) can have a large effect on the global discharge characteristics. One particular example concerns the formation of a dust void in the center of the discharge. At sufficiently high pulse energies, this formation of a dust free region - which occurs without laser irradiation—is totally suppressed. Moreover the experiments indicate that the laser pulses influence the early stages of the particle formation. Although the interaction between the laser and the plasma is not yet fully understood, it is remarkable that these localized nanosecond laser pulses can influence the plasma on a global scale. Besides new insights into fundamental problems, this phenomenon opens also new possibilities for the controlled manipulation of particle growth and particle transport in reactive plasmas.

HT6 108 Mode transitions and electronegativity in oxygen CCP and ICP* JUERGEN MEICHSNER, THOMAS WEGNER, *University of Greifswald* Mode transitions in 13.56 MHz oxygen radio frequency plasmas (CCP, ICP) and their impact on the electron heating mechanisms and electronegativity were studied by advanced plasma diagnostics. In particular, Langmuir probe measurements, Gaussian beam microwave interferometry (160 GHz) coupled with laser photodetachment of negative oxygen ions, as well as the (phase resolved) optical emission and VUV absorption spectroscopy, and ion mass spectrometry are taken into consideration. With increasing RF power a transition between high and low electronegativity was found both in CCP and ICP discharge configuration. Thereby, the changed electron heating mechanisms, e.g., the alpha-gamma mode transition in CCP and the E-H mode transition in ICP is combined with the change of electronegativity. In strongly asymmetric CCP at moderate pressure the emission of secondary negative ions at the powered electrode have to be considered, too. Thereby, pseudo secondary electrons may be produced due to collision detachment of negative ion by metastables. During the E-H mode transition in oxygen ICP, the increasing gas temperature and the metastables influences significantly the oxygen kinetics.

*Supported by the DFG Collaborative Research Centre Transregio 24 "Fundamentals of Complex Plasmas".

HT6 109 OTHER PLASMA SCIENCE TOPICS

HT6 110 Neutrosophic Triplet as extension of Matter Plasma, Unmatter Plasma, and Antimatter Plasma FLORENTIN SMARANDACHE, *University of New Mexico* MUMTAZ ALI, *Quaid-i-azam University Islamabad, Pakistan* A Neutrosophic Triplet, is a triplet of the form: <a, neut(a), and anti(a) >, where neut(a) is the neutral of a, i.e. an element (different from the identity element of the operation *) such that a*neut(a) = neut(a)*a = a, while anti(a) is the opposite of a, i.e. an element such that a*anti(a) = anti(a)*a = neut(a). Neutrosophy means not only indeterminacy, but also neutral (i.e. neither true nor false). For example we can have neutrosophic triplet semigroups, neutrosophic triplet loops, etc. As a particular case of the Neutrosophic Triple, in physics one has <Matter, Unmatter, Antimatter>and its corresponding triplet <Matter Plasma, Unmatter Plasma, Antimatter Plasma>. We further extended it to an m-valued refined neutrosophic triplet, in a similar way as it was done for T_1, T_2, ...; I_1, I_2, ...; F_1, F_2, ... (i.e. the refinement of neutrosophic components). We may have a neutrosophic m-tuple with respect to the element "a" in the following way: (a; $neut_1(a)$, $neut_2(a)$, ..., $neut_p(a)$; $anti_1(a)$, $anti_2(a)$, ..., $anti_p(a)$), where $m = 1+2p$, such that: - all $neut_1(a)$, $neut_2(a)$, ..., $neut_p(a)$ are distinct two by two, and each one is different from the unitary element with respect to the composition law *; - also $a*neut_1(a) = neut_1(a)*a = a$, $a*neut_2(a) = neut_2(a)*a = a, \ldots, a*neut_p(a) = neut_p(a)*a = a$; - and $a*anti_1(a) = anti_1(a)*a = neut_1(a)$, $a*anti_2(a) = anti_2(a)*a = neut2(a), \ldots, a*anti_p(a) = anti_p(a)*a = neut_p(a)$; - where all $anti_1(a)$, $anti_2(a)$, ..., $anti_p(a)$ are distinct two by two, and in case when there are duplicates, the duplicates are discarded.

HT6 111 Efficient Technique to Evaluate the Lindhard Dielectric Function LORENZO UGO ANCARANI, *Universite de Lorraine* HERVE JOUIN, *Universite de Bordeaux* Since the pioneering work of Lindhard, the dielectric response function obtained in [1] from first principles within the Random Phase Approximation (RPA) has been and is widely used in many areas of Physics such as Plasma Physics, Atomic Physics in plasmas, Solid State Physics, Plasmonics and Nuclear Physics. Indeed, the dielectric function is the fundamental ingredient for many theories related to the response of matter to an external perturbation characterized by a wavenumber k and a frequency ω. In all the above applications the Lindhard dielectric function has to be evaluated many times (for given temperature T, and given values of a real parameter which depends on k and ω). It is notorious that the integral defining its real part presents a logarithmic divergence which renders the numerical calculation delicate and time consuming. Through a simple but very efficient mathematical trick we are able to remove the singularity and obtain a useful integral expression which is trouble-free, i.e., it can be dealt with any standard numerical quadrature [2]. Our analytical expression greatly facilitates the computation of the dielectric function.

[1] J. Lindhard, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. **28**, 1 (1954).
[2] L. U. Ancarani and H. Jouin, Eur. Phys. J.-Plus **131**, 114 (2016).

HT6 112 Discharge-pumped XUV source* JIRI SCHMIDT, KAREL KOLACEK, JAROSLAV STRAUS, OLEKSANDR FROLOV, *Institute of Plasma Physics of the CAS* We have built two experimental devices (CAPEX and CAPEX-U) working as XUV sources, which are based on the fast, pinching capillary discharge. On both these devices we have observed lasing at 46.9 nm (Ne-like Ar line). However, besides lasing at the above mentioned relatively long wavelength, they are also used for testing a possibility of amplification at the wavelengths below 20 nm that have more practical applications. Particularly, at present nitrogen-filled capillary (?4 mm x 90 mm) discharge is studied for the development of XUV (soft X-ray) laser based on recombination pumping scheme: the fully stripped nitrogen nuclei recombine to hydrogen-like atoms, where Balmer-alpha transition (wavelength 13.4 nm) is - according to theoretical predictions - capable of creating population inversion. The modified electrical parameters (peak current $\sim$60 kA with quarter period of $\sim$45 ns) meet the necessary theoretical conditions. The only question remains, if suitable pre-pulse can suppress the capillary-wall-ablation, which in all presently known cases has quashed the amplification. In this paper the recent results obtained from both these discharge systems (argon-, nitrogen-filled capillaries) will be presented.

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HT6 113 Energy flux to substrate in high-power impulse magnetron sputtering measured by using optical low-coherence interferometry KATSUHIRO HATTORI, TAKAYUKI OHTA, *Meijo university* AKINORI ODA, *Chiba Institute of Technology* HIROYUKI KOUSAKA, *Nagoya University* MASAFUMI ITO, *Meijo university* The substrate during the plasma irradiation is heated by charged species, neutral species, and the heat radiation and the substrate temperature is determined by energy flux to the substrate. High-power impulse magnetron sputtering (HiPIMS) using short-pulse high-voltage promotes the ionization of sputtered atoms and realizes high density plasma. In this study, we measured the silicon substrate temperature with non-contact type substrate temperature measurement method using optical low-coherence interferometry(LCI) and elucidated the heating mechanisms of the substrate temperature in HiPIMS. The target material was Ti and the distance between the substrate and the target was 60mm. Ar is used as the sputtering gas. The pulse width was from 50 to 300 μsec, the pulse frequency was from 100 to 500Hz. Applied voltages were changed to be from -400V to -900V. Measurement accuracy of contact-type thermocouples and that of noncontact-type LCI were within 2 degree C and 0.7 degree C, respectively. The heat influx to the substrate was calculated from the temporal variation of substrate temperature base on the energy balance equation and increased with increasing applied voltage. The emission intensity of Ti ion increased with increasing applied voltage even though that of Ti atom was constant. These results suggested that main contribution of substrate heating is Ti ion bombardment.

HT6 114 Network structural analysis using directed graph for chemical reaction analysis in weakly-ionized plasmas KYOSUKE NOBUTO, YASUTAKA MIZUI, SHIGEYUKI MIYAGI, OSAMU SAKAI, *The University of Shiga Prefecture* TOMOYUKI MURAKAMI, *Seikei University* We visualize complicated chemical reaction systems in weakly-ionized plasmas by analysing network structure for chemical processes, and calculate some indexes by assuming interspecies relationships to be a network to clarify them. With the current social evolution, the mean size of general data which we can use in computers grows huge, and significance of the data analysis increases. The methods of the network analysis which we focus on in this study do not depend on a specific analysis target, but the field where it has been already applied is still limited. In this study, we analyse chemical reaction systems in plasmas for configuring the network structure. We visualize them by expressing a reaction system in a specific plasma by a directed graph and examine the indexes and the relations with the characteristic of the species in the reaction system. For example, in the methane plasma network, the centrality index reveals importance of CH_3 in an influential position of species in the reaction [1]. In addition, silane and atmospheric pressure plasmas can be also visualized in reaction networks, suggesting other characteristics in the centrality indexes.

[1] O. Sakai, K. Nobuto, S. Miyagi, and K. Tachibana, AIP Adv. **5**, 107140 (2015).

HT6 115 PLASMA APPLICATIONS

HT6 116 Simplification of the laser absorption process in the particle simulation for the laser-induced shockwave processing KOHEI SHIMAMURA, *University of Tsukuba* To reduce the computational cost in the particle method for the numerical simulation of the laser plasma, we examined the simplification of the laser absorption process. Because the laser frequency is sufficiently larger than the collision frequency between the electron and heavy particles, we assumed that the electron obtained the constant value from the laser irradiation. First of all, the simplification of the laser absorption process was verified by the comparison of the EEDF and the laser-absorptivity with PIC-FDTD method. Secondary, the laser plasma induced by TEA CO_2 laser in Argon atmosphere was modeled using the 1D3V DSMC method with the simplification of the laser-absorption. As a result, the LSDW was observed with the typical electron and neutral density distribution.

HT6 117 PLASMA ETCHING

HT6 118 Ribbon Ion Beam with Controlled Directionality and Local Reactive Chemistry COSTEL BILOIU, GLEN GILCHRIST, ALEX KONTOS, SOLOMON BASAME, TYLER ROCKWELL, CHRIS CAMPBELL, KEVIN DANIELS, ERNEST ALLEN, JAY WALLACE, JON BALLOU, RICHARD HERTEL, TSUNG-LIANG CHEN, SHURONG LIANG, VIKRAM SINGH, *Applied Materials* A plasma processing technology designed for etch of 3D semiconductor structures is presented. The technology is characterized by controllable ion directionality and local reactive chemistry and it is based on proprietary Applied Materials – Varian Semiconductor Equipment ribbon ion beam architecture. It uses a combination of inert gas ion beam and injection of reactive chemical species at the Point-of-Use (PoU), i.e., at the wafer surface. The ion source uses an inductively coupled plasma source and a diode-type extraction optics. A beam shaping electrode allows extraction of two symmetrical ribbon-like beamlets. The ion beam has in situ controllable ion angular distribution in both mean angle and angular spread. The beam has a uniform distribution of beam current and angles over a waist exceeding 300 mm, allowing full wafer processing in one pass. Chemical compounds are delivered at PoU through linear shower heads. The reactive chemical compound delivered in this fashion maintains its molecular integrity. This result in protection of the trench side walls from deposition of etch residue and facilitates formation of volatile byproducts. The technology was used successfully for mitigation of Magnetic Tunel Junction etch residue. Other applications were this technology differentiate from present technologies are contact liner etch, Co recess, and 1D hole elongation.

HT6 119 Plasma Treatment of Metal Surface by Runaway Electrons Preionized Diffuse Discharge* VICTOR TARASENKO, *Head of laboratory* MICHAEL EROFEEV, *researcher* VASILII RIPENKO, *post-doctor* MIKHAIL SHULEPOV, *junior researcher* INSTITUTE OF HIGH CURRENT ELECTRONICS COLLABORATION,† NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY COLLABORATION‡ In this work we present experimental results on the generation of diffuse discharge initiated by runaway electron beam and X-rays in pulsed-periodic mode in nitrogen at atmospheric pressure, and its application for metal surface modification. The aim of this work is to investigate the possibilities of surface modification of copper, stainless steel, aluminum, niobium and titanium in the plasma of REP DD, formed in nitrogen flow. The study shows that REP DD treatment after exposure of 100000 shots provides ultrafine surface cleaning of all metals from carbon contamination. At the same time, it is found that all materials subjected to REP DD are involved in surface oxidation. Moreover, the surface energy of the treated specimens increased up to 4 times, whereas the other surface properties like microhardness or roughness remain almost unchanged. Thus, plasma treatment by runaway electron preionized diffuse discharge has enabled us to create an optimum metal surface without mechanical damages that is important for further coating, printing, painting, and adhesive bonding.

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HT6 120 Plasma Etching of superconducting radio frequency cavity by Ar/Cl_2 capacitively coupled Plasma JANARDAN UPADHYAY, SVETOZAR POPOVIC, *Old Dominion University* ANNE-MARIE VALENTE-FELICIANO, LARRY PHILLIPS, *Jefferson Lab* LEPSHA VUSKOVIC, *Old Dominion University* We are developing plasma processing technology of superconducting radio frequency (SRF) cavities. The formation of dc self-biases due to surface area asymmetry in this type of plasma and its variation on the pressure, rf power and gas composition was measured. Enhancing the surface area of the inner electrode to reduce the asymmetry was studied by changing the contour of the inner electrode. The optimized contour of the electrode based on these measurements was chosen for SRF cavity processing. To test the effect of the plasma etching on the cavity rf performance, a 1497 MHz single cell SRF cavity is used, which previously mechanically polished, buffer chemically etched afterwards and rf tested at cryogenic temperatures for a baseline test. Plasma processing was accomplished by moving axially the inner electrode and the gas flow inlet in a step-wise manner to establish segmented plasma processing. The cavity is rf tested afterwards at cryogenic temperatures. The rf test and surface condition results are presented.

HT6 121 PLASMA DEPOSITION

HT6 122 Characterization of graded TiC layers deposited by HiPIMS method* JANA BOHOVICOVA, LUCIA BONOVA, JURAJ HALANDA, JOZEF IVAN, MARCEL MESKO, *Slovak University of Technology* ADVANCED TECHNOLOGIES RESEARCH INSTITUTE TEAM, INSTITUTE OF ELECTRONIC AND PHOTONIC TEAM An advanced yet recent development of sputter technique is high power impulse magnetron sputtering (HiPIMS), in which short, energetic pulses are applied to the target, leading to a formation of an ultra-dense plasma in front of the cathode, that provide a high degree of ionization of sputtered material, and consequently enable to control the energy and the direction of the deposition flux. This gives a possibility to alter composition and microstructure in a controlled manner, enables the optimization of TiC for tribological applications. The aim of this work is to link physical phenomena in transient HiPIMS discharges to microstructural and compositional properties of graded TiC thin films. It was found that Ti bottom layer is contamination free. Compared to the direct current magnetron sputtering films, we observed an element specific reduction of impurities measured by ERDA by a factor 3 for N, 4 for H and by a factor of 20 for O. The high purity of Ti layer is partly explained by gas rarefaction and the cleaning effect of the bombarding ions. Graphitization degree of carbon top layer was elucidated by Raman spectroscopy. The compositional effects are correlated with differences in the film microstructure revealed by SEM, XRD and TEM analysis.

*This work was supported by VEGA, Project No. 1/0503/15 and APVV, Project No. 15-0168.

HT6 123 Investigation of the synthesized graphene on the copper foil depending on the plasma condition HYUNJAE PARK, *National fusion research institute* JIN-HA SHIN, *Sungkyunkwan University* GANG-IL LEE, YONG HO JUNG, YONG SUP CHOI, *National fusion research institute* YOUNG IL SONG, *Sungkyunkwan University* PLASMA TECHNOLOGY RESEARCH CENTER TEAM, ADVANCED MATERIALS AND PROCESS RESEARCH CENTER TEAM In this study, direct growth of graphene nanowalls (GNWs) synthesized by electron cyclotron resonance (ECR) plasma on Cu foil at low temperature. The direct growth method is simplified manufacturing process and avoid damages and contaminants from graphene transfer process. The density and temperature of plasma were measured using Cylindrical Langmuir probe analysis. Using the Residual Gas Analyzer (RGA, SRS200) for the generated gas analysis by plasma conditions. The morphologies and structures of GNWs were characterized by field-emission scattering electron microscope (FESEM), Transmission electron microscopy

(TEM), 3D optical measurement system and Raman spectra measurement.

HT6 124 Solid coatings deposited from liquid methyl methacrylate via Plasma Polymerization LISA WURLITZER, WOLFGANG MAUS-FRIEDRICHS, SEBASTIAN DAHLE, *Clausthal University of Technology* The polymerization of methyl methacrylate via plasma discharges is well known today. Usually, plasma-enhanced chemical vapor deposition (PECVD) is used to deposit polymer coatings. Solid coatings are formed out of the liquid phase from methyl methacrylate via dielectric barrier discharge. The formation of the coating proceeds in the gas and the liquid phase. To learn more about the reactions in the two phases, the coatings from MMA monomer will be compared to those from MMA resin. Finally, attenuated total reflection infrared spectroscopy, confocal laser scanning microscopy and X-ray photoelectron spectroscopy are employed to characterize the solid coatings. In conclusion, the plasma enhanced chemical solution deposition is compared to the classical thermal polymerization of MMA.

HT6 125 Measurement of dielectric-film thickness at low density plasma SANG-BUM JEON, *Department of Electrical Engineering, Hanyang University, South Korea* DONG-HWAN KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University, South Korea* JIN-YONG KIM, SE-YEOL PAEK, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, South Korea* The measurement system of dielectric-film thickness was improved to measure thin-film at low density plasma. There are three improvements than previous method, which is electrical measurement of dielectric-film thickness using R-C sheath model. First, the frequency of input voltage was decreased to reduce the ratio of the dielectric-film impedance to sheath impedance. Second, three different frequencies were used to overcome the inaccuracy of measured phase; only amplitudes of measured current were used to obtain a film thickness. Third, the notch filter was used for sensing current instead of the resistor to improve the signal to noise ratio. Using this method, dielectric-film thickness was well measured at low density plasma (thickness: ~300, sheath impedance: 100~200 kΩ).

HT6 126 GREEN PLASMA TECHNOLOGIES: ENVIRONMENTAL AND ENERGY APPLICATIONS

HT6 127 Temporally resolved plasma spectroscopy for analyzing natural gas components KAZUNOBU KOBAYASHI, *Osaka Gas Co., Ltd.* NAOMASA TSUMAKI, TSUYOHITO ITO, *Osaka University* Temporally resolved plasma spectroscopy has been carried out in two different hydrocarbon gas mixtures (CH_4/Ar and C_2H_6/Ar) to explore the possibility of a new gas sensor using plasma emission spectral analysis. In this experiment, a nanosecond-pulsed plasma discharge was applied to observe optical emissions representing the initial molecular structure. It is found that a CH emission intensity in CH_4/Ar is higher than that in C_2H_6/Ar. On the other hand, C_2 intensities are almost the same degree between CH_4/Ar and C_2H_6/Ar. This finding indicates that the emission intensity ratio of CH to C_2 might be an effective index for a gas analysis. In addition, a time for the highest emission intensities of CH and C_2 is several nanoseconds later than that of Ar. This result suggests that spectra from the initial molecular structure may be observed at the early stage of the discharge before molecules are fully dissociated, and this is currently in progress.

HT6 128 Conversion of high-pressure carbon dioxide by laser-induced plasma TAKU GOTO, HIROTAKA SUZUKI, MASATO KOIZUMI, TSUYOHITO ITO, *Osaka University* In the conversion process of CO_2 ->CO + 1/2 O_2 by means of plasma, an atomic oxygen is often observed as the intermediate state. As the following reaction forming 1/2 O_2 from O is exothermic, unless the energy is reused, the existence of O atoms results in a lower conversion efficiency of the process. Thus, we are trying to find a pathway which forms 1/2 O_2 directly, by contribution of the high pressure, which hopefully boosts the conversion efficiency. In this study, we produce plasma by nanosecond-pulsed laser focused on various metallic targets (Sn, Zn and Cu) in pressurized CO_2 environments. The results indicate that the energy conversion efficiency depends on the pressure. In addition, applying a target results in a higher energy conversion efficiency than that without targets, and the efficiency depends on the target materials. We currently believe that the target materials modify the initial density of plasma and the pressure controls the following plasma dynamics. The details will be presented at the conference.

HT6 129 The purification mechanism of wastewater by underwater discharge KANGIL KIM, SUK HWAL MA, JIN YOUNG HUH, YONG CHEOL HONG, *National Fusion Research Institute* NATIONAL FUSION RESEARCH INSTITUTE TEAM, CHONBUK NATIONAL UNIVERSITY TEAM, KWANGWOON UNIVERSITY TEAM, NPAC TEAM There is a continuing need for development of effective, cheap and environmentally friendly processes for purification of wastewater. In this regard, the plasmas can be a promising candidate for next-generation method to purify the wastewater. It is well known that the plasmas generate many reactive species and thus they are predominant for degradation of organic pollutants from water. In order to generate plasma in wastewater, the capillary electrodes are used with ac power supply. After plasma treatment, the coagulants are added to purify the wastewater. The efficiency of coagulation is significantly improved by plasma treatment of wastewater. These results may come from the reactions among radicals of plasma-treated water, electron reduction and oxidation of ions in waste water, and coagulant. In order to verify the hypothesis, we measured characteristics changes of water by underwater discharge. In this study, we propose the purification mechanism of wastewater by underwater discharge. We expect that the underwater discharge can be applied to purify wastewater in near future.

HT6 130 EMF generation in low-temperature plasma* ALEXANDER PAL, VALERY BABICHEV, NIKOLAY DYATKO, ANATOLY FILIPPOV, ANDREY STAROSTIN, *SRC RF Troitsk Institute for Innovation and Fusion Research, 142190 Troitsk, Moscow, Russia* EMF generation in plasma created by an *e*-beam in electropositive gases at atmospheric pressure was investigated experimentally and numerically. It was found that propagation of 120 keV *e*-beam with cross-section 1.2×2 cm^2 and current of 240 μA through argon at 10^5 Pa gas pressure between an aluminum exit window and an iron collector was followed by 360 μA current of opposite direction. A numerical modeling of the current flux was performed in an one-dimensional approximation along the axis z in the direction of *e*-beam propagation. It is seen, that the current density grows with increasing the ionization rate and the largest effect takes place in argon. The discovered effect of the current flux is determined by nonuniform gas ionization resulting in different diffusion electron fluxes near different electrodes and, therefore, in different near-electrodes potential falls. This difference creates a steady current flux in the inter-electrode gap. The mechanism of EMF generation is analogous to the Dember effect at the nonuniform photoexcitation of semiconductors.

*The work was supported by the Russian Science Foundation, Project No. 16-12-10511.

HT6 131 BIOLOGICAL APPLICATIONS OF PLASMAS

HT6 132 Effect of sheath gas in atmospheric-pressure plasma jet for potato sprouting suppression S. NISHIYAMA, M. MONMA, K. SASAKI, *Hokkaido University* Recently, low-temperature atmospheric-pressure plasma jets (APPJs) attract much interest for medical and agricultural applications. We try to apply APPJs for the suppression of potato sprouting in the long-term storage. In this study, we investigated the effect of sheath gas in APPJ on the suppression efficiency of the potato sprouting. Our APPJ was composed of an insulated thin wire electrode, a glass tube, a grounded electrode which was wound on the glass tube, and a sheath gas nozzle which was attached at the end of the glass tube. The wire electrode was connected to a rectangular-waveform power supply at a frequency of 3 kHz and a voltage of ± 7 kV. Helium was fed through the glass tube, while we tested dry nitrogen, humid nitrogen, and oxygen as the sheath gas. Eyes of potatoes were irradiated by APPJ for 60 seconds. The sprouting probability was evaluated at two weeks after the plasma irradiation. The sprouting probability was 28% when we employed no sheath gases, whereas an improved probability of 10% was obtained when we applied dry nitrogen as the sheath gas. Optical emission spectroscopy was carried out to diagnose the plasma jet. It was suggested that reactive species originated from nitrogen worked for the efficient suppression of the potato sprouting.

HT6 133 Cysteine as a Biological Probe for Comparing Plasma Sources* JAN-WILM LACKMANN, *Biomedical Applications of Plasma Tech., Ruhr Univ Bochum* JUDITH GOLDA, *Experimental Physics II, Ruhr Univ Bochum* FRIEDERIKE KOGELHEIDE, *Biomedical Applications of Plasma Tech., Ruhr Univ Bochum* JULIAN HELD, VOLKER SCHULZ-VON-DER-GATHEN, *Experimental Physics II, Ruhr Univ Bochum* KATHARINA STAPELMANN, *Biomedical Applications of Plasma Tech., Ruhr Univ Bochum* A large variety of plasma sources are available in the plasma medicine community. While enabling to choose the most promising source for a certain biomedical application, comparison of the different sources with a focus on their effect on biological targets is rather challenging. To allow for better comparison of various sources, the recent European COST action MP1101 was used to design the COST reference microplasma jet [1]. Cysteine is a promising candidate investigate the impact of plasma from various sources on a standardized biological molecule, which is especially relevant for the investigations on a molecular level after plasma treatment. The simple structure of cysteine allows for a more in-depth analysis of each chemical group after plasma treatment and enables a comparison between different plasma sources and treatment parameters on each chemical group. The model itself has already been successfully established using a dielectric barrier discharge [2]. Here, additional plasma sources are compared by the means of their impact on cysteine samples, showing e.g. the influence of feed-gas variations by adding oxygen or nitrogen admixture

*This work was supported by the German Research Foundation (DFG) with the packet grant PAK816 (PlaCID).

[1]J. Golda *et al.*, J. Phys. D **49**, 084003.
[2]F. Kogelheide *et al.*, J. Phys. D **49**, 084004.

HT6 134 Promotion of cell proliferation using atmospheric-pressure radical source* MASAFUMI ITO, MASASHI OKACHI, TAKAYOSHI KOIZUMI, JUN-SEOK OH, *Meijo University* HIROSHI HASHIZUME, *Nagoya University* TOMIYASU MURATA, *Meijo University* MASARU HORI, *Nagoya University* In this study, we have focused on the effects of neutral radicals on cell proliferation and treated budding yeasts and mouse fibroblast cells in solutions using neutral radical source, which can selectively supply neutral radicals without charged species and optical emissions. The activation and inactivation effects of neutral oxygen or nitrogen-oxide radicals on cells were investigated using a cell count and a colony count method, respectively. The radical densities supplied from the radical source were measured using VUVAS and UVAS. Based on the measurements of free residual chloride and hydrogen peroxide concentrations in the solutions treated with radicals, we have investigated their effects on the activation and the inactivation. From these results, we have concluded that the main factor for the inactivation in PBS solutions is due to the hypochlorous acid generated in the PBS irradiated with oxygen radicals. On the other hand, we have found that the main factor for the promotion is not the hypochlorous acid but other radicals.

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HT6 135 PLASMA PROPULSION AND AERODYNAMICS

HT6 136 Ion acceleration in electrodeless plasma thrusters TREVOR LAFLEUR, *LPP Ecole Polytechnique, and Centre National d'Etudes Spatiale (CNES)* FELIX CANNAT, *Mars-Space* JULIEN JARRIGE, PAUL-QUENTIN ELIAS, DENIS PACKAN, *ONERA-The French Aerospace Lab* Since electrodeless plasma thrusters do not use biased electrodes or grids to accelerate ions, it is unclear what determines the magnitude of the "accelerating voltage" and hence what the ion beam energy is. In this work a combined theoretical/experimental study of the relationship between the electron temperature and the ion energy was performed to provide such an answer. Experimental measurements show that the ion energy and electron temperature are strongly correlated, and demonstrate that the driving force for the plasma expansion in magnetic nozzles is the electron pressure: in complete analogy to chemical rockets with physical nozzles. Because there are no electrodes or applied voltages, the plasma that exits the thruster must be current-free, and we show that this establishes a strong criterion that determines the maximum accelerating potential that self-forms in the plasma. This maximum accelerating potential (which is between about 4-6 times the electron temperature) is similar to that which develops for a floating sheath, and depends on the electron velocity distribution function. Based on plasma loss considerations inside the thruster cavity, and the drop-off of the ionization cross section for large electron energies in most gases, we predict a theoretical maximum achievable ion beam energy of about 400 eV for argon and xenon propellants.

HT6 137 Dynamic stall control by plasma actuators with combined energy/momentum action ANDREY STARIKOVSKIY, RICHARD MILES, *Princeton University* PU TEAM Increased interest in plasma assisted flow control is reflected by a dramatic increase in publication rate over the past decade, including numerous demonstrations of plasma-assisted flow control. Many of these have been summarized in several topical reviews published recently. As an alternative to AC voltage inputs, nanosecond pulse driven plasma actuators in which voltage is applied in pulses at a specific frequency and with a specific on-time have been proposed for separated flow control. Nanosecond pulsed periodic dielectric barrier devices have been experimentally demonstrated to affect separated flows over a range of Mach numbers ($0.03 \geqslant M \geqslant 0.85$) and Reynolds numbers ($10^{-4} \geqslant Re \geqslant 2 \times 10^{-6}$) that are consistent with retreating blade flows. Furthermore, the nanosecond pulsed actuators tested to date have required less than 10 Watt per cm. of wing span, and therefore are energy efficient.

HT6 138 Plasma guiding and deflection of high speed projectiles ANDREY STARIKOVSKIY, RICHARD MILES, *Princeton University* PU TEAM The deposition of energy in the air in front of a high-speed projectile can lead to both the reduction of drag and the production of steering moments. Modeling has shown that the major contributor to the drag reduction and the steering moment is the high temperature, low density region that is produced by the energy addition. If the energy addition is off axis, it leads to a non symmetric pressure distribution on the projectile as it passes through this region, producing steering control authority that increases nonlinearly with Mach number. Experiments with a tethered projectile and subsequently with a rotating projectile using pulsed laser energy addition were reported. More recent experiments with a 30-mm diameter projectile in M=3.5 flow have been undertaken using a nozzle driven by a pulsed shock tunnel 9.5 m in length and 100 mm internal diameter. Energy was deposited by Nd-YAG laser with pulse energy of about 3 Joules at 1064nm. The laser pulse duration was 5-6 ns. Preliminary results indicate that the laser spark – flow interaction changes the angular momentum of the model for with a laser pulse energy of 2.85 J, the angle between laser spark axis and the flow 30^{-0} and a flow speed 1100 m/s.

HT6 139 Effect of segmented electrode length on the performances of Hall thruster PING DUAN, LONG CHEN, GUANGRUI LIU, XINGYU BIAN, YAN YIN, *Dalian Maritime University* The influences of the low-emissive graphite segmented electrode placed near the channel exit on the discharge characteristics of Hall thruster are studied using the particle-in-cell method. A two-dimensional physical model is established according to the Hall thruster discharge channel configuration. The effects of electrode length on potential, ion density, electron temperature, ionization rate and discharge current are investigated. It is found that, with the increasing of segmented electrode length, the equipotential lines bend towards the channel exit, and approximately parallel to the wall at the channel surface, radial velocity and radial flow of ions are increased, and the electron temperature is also enhanced. Due to the conductive characteristic of electrodes, the radial electric field and the axial electron conductivity near the wall are enhanced, and the probability of the electron-atom ionization is reduced, which leads to the degradation of ionization rate in discharge channel. However, the interaction between electrons and the wall enhances the near wall conductivity, therefore the discharge current grows along with the segmented electrode length, and the performance of the thruster is also affected.

HT6 140 Effect of plasma distribution on propulsion performance in electrodeless plasma thrusters YOSHINORI TAKAO, KAZUKI TAKASE, *Yokohama National University* KAZUNORI TAKAHASHI, *Tohoku University* A helicon plasma thruster consisting of a helicon plasma source and a magnetic nozzle is one of the candidates for long-lifetime thrusters because no electrodes are employed to generate or accelerate plasma. A recent experiment, however, detected the non-negligible axial momentum lost to the lateral wall boundary, which degrades thruster performance, when the source was operated with highly ionized gases. To investigate this mechanism, we have conducted two-dimensional axisymmetric particle-in-cell (PIC) simulations with the neutral distribution obtained by Direct Simulation Monte Carlo (DSMC) method. The numerical results have indicated that the axially asymmetric profiles of the plasma density and potential are obtained when the strong decay of neutrals occurs at the source downstream. This asymmetric potential profile leads to the accelerated ion towards the lateral wall, leading to the non-negligible net axial force in the opposite direction of the thrust. Hence, to reduce this asymmetric profile by increasing the neutral density at downstream and/or by confining plasma with external magnetic field would result in improvement of the propulsion performance. These effects are also analyzed by PIC/DSMC simulations.

HT6 141 Measurement of Velocity Induced by a Propagating Arc Magnetohydrodynamic Plasma Actuator* YOUNG JOON CHOI, MILES GRAY, JAYANT SIROHI, LAXMINARAYAN RAJA, *The University of Texas at Austin* Plasma actuators can substantially improve the maneuverability and efficiency of aerial vehicles. These solid state devices have low mass, small volume, and high bandwidth that make them excellent alternatives to conventional mechanical actuators. In particular, a Rail Plasma Actuator (RailPAc) has the potential to delay flow separation on an aerodynamic surface by generating a large body force. A RailPAc consists of parallel rails and an electrical arc that propagates along the rails with a self-induced Lorentz force. The motion of the arc transfers momentum to the surrounding neutral air. A study was conducted to understand how the motion and shape of a propagating arc couples with the fluid momentum. In particular, we used Particle Imaging Velocimetry (PIV) and seedless PIV based on Background Oriented Schlieren (BOS) technique to measure the induced velocity of a propagating arc in one atmosphere. Results obtained provide insight into how the flow field responds to the passage of a RailPAc electrical arc. A complete description of the RailPAc actuation mechanism can be obtained if the fluid momentum measurements from PIV and seedless PIV are compared to the transit characteristics of an arc.

*US ARL Grant W911NF1410226.

SESSION JW1: ANTIMATTER COLLISIONS AND IONIZATION PROCESSES

Wednesday Morning, 12 October 2016; Room: 1 at 8:30; Allan Stauffer, York University, presiding

Invited Papers

8:30

JW1 1 Collisions involving Antimatter*

GAETANA LARICCHIA, *UCL*

Much progress in the understanding of the interactions between the matter and antimatter has been achieved through studies of collisions of positrons and positronium (Ps, the short-lived atom made of an electron and a positron) with atoms and molecules. In this talk, the focus will be on recent experiments performed at UCL concerning positronium formation [e.g. 1-3] and its scattering [e.g. 4-6]. Studies have now progressed to an exciting new phase. The finding of a similarity between the scattering probabilities of positronium and equivelocity electrons [5] has guided towards the observation of positronium resonant scattering [6] and the development of a positronium beam at incident energies below its break-up threshold [4], allowing searches in an energy regime which, for electrons, is rich in subtle quantum mechanical effects, including "target transparency" [4]. Possible avenues of future exploration will be indicated.

*The EPRSC is thanked for supporting positron research at UCL.

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[2]D. A. Cooke, D. J. Murtagh, and G. Laricchia, Phys. Rev. Lett. **104**, 073201 (2010).

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Contributed Papers

9:00

JW1 2 Stationary wave-packet continuum-discretization approach to differential ionization in antiproton-hydrogen collisions ILKHOM ABDURAKHMANOV, ALISHER KADYROV, IGOR BRAY, *Department of Physics, Astronomy and Medical Radiation Sciences, Curtin University, Australia* A novel single-center close-coupling approach to differential ionization in antiproton-hydrogen collisions has been developed. The continuous spectrum of the target has been discretized using stationary wave packets constructed from the Coulomb wave functions, the eigenstates of the target Hamiltonian. Such continuum discretization allows one to generate pseudostates with arbitrary energies and distribution which is ideal for detailed differential ionization studies. A comprehensive set of benchmark results from integrated to fully differential cross sections for antiproton-impact ionization of hydrogen in a wide energy range is provided. Contrary to previous predictions, we find that at low incident energies the singly differential cross section has a maximum away from zero emission energy. This feature could not be seen without a fine discretization of the low-energy part of the continuum. The ability of the proposed approach to generate target states with arbitrary energies and distribution is ideal for studies of ion-atom collisions where two-center rearrangement processes take place. Studies of those systems in the most detailed fully differential level will shed a light on the issues of double-counting of the continuum associated with the two-center expansion basis.

Invited Papers

9:15

JW1 3 A Sturmian approach for ionization processes of atoms and molecules*

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

The Sturmian approach, using Generalized Sturmian Functions (GSF), is a spectral method that has been applied successfully both for structure calculations [1] and for the study of several ionization processes [2] with atomic targets. GSF are two-body functions that solve a Sturm-Liouville problem. They can be used as a basis set to deal with two- or three-body bound or scattering problems. By construction, the whole GSF set can be chosen to possess asymptotic conditions appropriate for the physical problem under consideration: bound-type behavior with a specific asymptotic charge are chosen for bound states, while – for example - outgoing behavior with a given adequate energy are taken for solving scattering processes. This important intrinsic property makes GSF basis sets - and thus the whole approach - computationally efficient. In the case of ionization, a specific feature of our methodology is that the scattering amplitude and the corresponding cross section are extracted directly from the asymptotic part of the scattering function without requiring the evaluation of a matrix element. Compared to the case of many-electron atoms several extra challenges occur for molecules: the scattering problem is generally multicenter and highly non-central, and the molecular orientation must also be taken into account. These features make the computational task much more cumbersome and expensive than for atomic targets. The Sturmian

approach with GSF has been recently extended and implemented to study single ionization of small polyatomic molecules by photon and electron impact [3]. Results for a variety of single and double ionization processes will be presented.

*This work has been done in collaboration with G. Gasaneo, D.M. Mitnik, J.M. Randazzo, F.D. Colavecchia, M.J. Ambrosio, J.A. Del Punta and C.M. Granados-Castro. We would like to acknowledge the CNRS funding (PICS project N. 06304).

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Contributed Papers

9:45

JW1 4 Fluctuation capture in dense gases and liquids - trapping, detrapping and non-equilibrium transport DANIEL COCKS, RON WHITE, *James Cook University* When charged particles travel through a background of a dense gas or liquid the correlations in the fluid significantly modify the transport of the charged particle. In particular, a new process becomes available, in which the particle is captured into a local fluctuation (bubble or cluster) of the fluid. The trapping has an influence on all transport coefficients, especially annihilation rates of positrons and positronium. Understanding fluctuation capture is important in medical diagnostics, therapy and particle detectors in the low-energy regime, but has so far been unable to be accounted for in transport simulations. We present a new framework that produces energy-resolved "capture cross sections" $\sigma_{cap}(\epsilon)$ along with "waiting time distributions" $\Theta(t)$ which allow transport theories to include capture as a process. We demonstrate good agreement between our ab initio calculations and experimental measurements of electrons and positrons in dense noble-gas fluids.

SESSION JW2: CAPACITIVELY COUPLED PLASMAS II

Wednesday Morning, 12 October 2016; Room: 2a at 8:30; Shahid Rauf, Applied Materials Inc, presiding

Invited Papers

8:30

JW2 1 Experimental and simulation study of capacitively coupled electronegative discharges
ARANKA DERZSI, *Wigner Research Centre for Physics, Budapest, Hungary*

The application of tailored voltage waveforms, generated by using multiple harmonics of a base frequency, for the excitation of capacitive RF discharges has been recently introduced as a new method to control the ion flux and ion energy distribution at the electrodes. In plasma processing of surfaces complex mixtures of electronegative, reactive gases (e.g. CF_4, O_2) are usually required. Therefore, the question of whether this new approach to control ion properties can be applied efficiently to such systems is of exceptional importance. Here the electron heating and ionization dynamics, the possibilities and limitations of the efficient control of plasma parameters by voltage waveform tailoring in low-pressure capacitively coupled electronegative discharges are presented. The focus is on geometrically symmetric O_2 plasmas, which are investigated by PIC/MCC simulations and experimental methods. O_2 discharges driven by impulse-type and sawtooth-type voltage waveforms composed of a maximum of four consecutive harmonics are studied. Experimental results on the dc self-bias voltage, as well as the spatiotemporal distribution of the plasma emission are compared with simulation data for a wide range of operating conditions (fundamental driving frequencies of 5 MHz – 15 MHz, at pressures of 50 mTorr – 700 mTorr). Transitions between electron power absorption due to sheath expansion and the drift-ambipolar mode were induced both by changing the number of harmonics or by changing the gas pressure. A good agreement between simulation and experiment is found, which shows that the collision-reaction model for O_2 discharges underlying the simulations describes reasonably the complicated chemistry of oxygen plasmas. An investigation of the dependence of the discharge characteristics on the surface destruction coefficient of the $O_2(a^1\Delta_g)$ singlet metastable molecules revealed the crucial role of these species, which strongly affects the negative ion balance of the plasma.

Contributed Papers

9:00

JW2 2 Plasma Self-organization in Moderately High Pressure Capacitively Coupled RF Discharge ANTON KOBELEV, *Applied Materials, Inc., Global Development Center, Russia* KALLOL BERA, JOHN FORSTER, *Applied Materials, Inc.* ALEXANDER SMIRNOV, *Applied Materials, Inc., Global Development Center, Russia* Numerical simulation and experimental study of plasma self-organization in rf capacitively coupled discharge consisting of conductive plate with the rows of holes or slots between powered and return electrodes have been performed. It has been observed experimentally that there is a set of holes with increased luminosity in an almost periodic manner separated by darker holes in Ar discharge at 13.56 MHz at moderately high pressure (a few Torr). Two-dimensional Ar and He plasma simulations have been performed using electron kinetic model with non-local approach for multiple slots in the conductive plate. The result for Ar plasma shows that an initial perturbation of plasma density inside one slot increases, if initial perturbation is two times higher than that inside the rest of slots. The electron current enhances in this one slot that affects neighboring slots. Increase in electron current increases power deposition, and enhances plasma density further in this slot. If plasma density perturbation is increased in three neighboring slots, the perturbations inside all slots except one are damped. The slot with strong plasma density affects up to eight neighboring slots, which is close to periodicity observed experimentally. For He plasma, initial perturbation inside the slot dies down similar to experimental observation.

9:15

JW2 3 Comparison of different methods for the measurements and calculations of Capacitively Coupled Plasmas electrical characteristics GIANNIS TSIGARAS, *Plasma Technology Laboratory - Department of Chemical Engineering - University of Patras* NIKOLAOS SPILIOPOULOS, *Department of Physics - University of Patras* ELEFTHERIOS AMANATIDES, DIMITRIOS MATARAS, *Plasma Technology Laboratory - Department of Chemical Engineering - University of Patras* PLASMA TECHNOLOGY LABORATORY - DEPARTMENT OF CHEMICAL ENGINEERING - UNIVERSITY OF PATRAS TEAM Despite the steps forward in the plasma processing of materials, there are still open issues concerning the design of plasma systems and the effective control of plasma parameters. In this work, a comparison between different methods for the measurement and calculation of discharge electrical characteristics is presented. The measurements were accomplished in a laboratory scale cylindrical 13.56 MHz CCP reactor and three different methods were tested: (a) A two port network based technique (b) A distributed element model method and (c) A method based on the solution of the wave equation. The differences between the results of these techniques are discussed in terms of the assumptions that are adopted in each of them. Moreover, the effect of electrode geometry on plasma electrical and microscopic properties was investigated. Two different electrodes were used and changes on the power transfer, plasma current and impedance were monitored together with variations of spatiotemporal emission in 13.56 MHz Ar discharges. Finally, the calculated delivered power error as a function of small measured errors for each method is presented.

9:30

JW2 4 Fluid Modeling of a Very High Frequency Capacitively Coupled Reactor ROCHAN UPADHYAY, *Esgee Technologies Inc.* LAXMINARAYAN RAJA, *The University of Texas at Austin* PETER VENTZEK, *Tokyo Electron America* TOSHIHIKO IWAO, KIYOTAKA ISHIBASHI, *Tokyo Electron Ltd.* ESGEE TECHNOLOGIES INC. COLLABORATION, THE UNIVERSITY OF TEXAS AT AUSTIN COLLABORATION, TOKYO ELECTRON LTD. COLLABORATION Very High Frequency Capacitively Coupled Plasma (VHF-CCP) discharges have been studied extensively for semiconductor manufacturing applications for well over a decade. Modeling of these discharges however poses significant challenges owing to complexity associated with simulation of multiple coupled phenomena (electro-static/magnetic fields and plasma physics) over different scales and the representation of these phenomena in a computational framework. We present 2D simulations of a self-consistent plasma with the electromagnetic field represented using vector and scalar potentials. For a range of operating conditions, the ratio of capacitive and inductive power, calculated using empirical correlations available in the literature, are matched by adjusting both the electrostatic and electromagnetic fields in a decoupled manner. We present results using this model that demonstrate most of the important VHF-CCP discharge phenomena reported in the literature, such as electromagnetic wave versus electrostatic heating and its impact on plasma non-uniformity, wave resonances, etc. while realizing a practically feasible computational model.

9:45

JW2 5 Consistent kinetic simulation of plasma and sputtering in low temperature plasmas* FREDERIK SCHMIDT, JAN TRIESCHMANN, THOMAS MUSSENBROCK, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum* Plasmas are commonly used in sputtering applications for the deposition of thin films. Although magnetron sources are a prominent choice, capacitively coupled plasmas have certain advantages (e.g., sputtering of non-conducting and/or ferromagnetic materials, aside of excellent control of the ion energy distribution). In order to understand the collective plasma and sputtering dynamics, a kinetic simulation model is helpful. Particle-in-Cell has been proven to be successful in simulating the plasma dynamics, while the Test-Multi-Particle-Method can be used to describe the sputtered neutral species. In this talk a consistent combination of these methods is presented by consistently coupling the simulated ion flux as input to a neutral particle transport model. The combined model is used to simulate and discuss the spatially dependent densities, fluxes and velocity distributions of all particles.

*This work is supported by the German Research Foundation (DFG) in the frame of Transregional Collaborative Research Center (SFB) TR-87.

SESSION JW3: ATMOSPHERIC PLASMA JETS AND SOURCES I
Wednesday Morning, 12 October 2016; Room: 2b at 8:30;

Invited Papers

8:30

JW3 1 Attraction of positive streamers to surfaces and free electrons
SANDER NIJDAM, *Eindhoven University of Technology*

Positive streamers require two ingredients to propagate: a sufficiently high external electric field and a constant supply of (free) electrons in front of the developing streamer head. In air, the electrons are usually provided by photo-ionization, producing free electrons in all directions around the streamer head. However, in cases with reduced photo-ionization, for example in pure gasses, the local external field direction does not necessarily coincide with the direction of sufficient electron density. One way to create such a condition is by using a laser beam to ionize a path. Depending on parameters this can lead to a guided streamer moving almost perpendicular to the field direction. Alternatively, a preceding discharge can have left a specific electron distribution and thereby guide the path of following discharges. This effect is very important for pulsed plasma jets or plasma bullets in pure nitrogen. We have studied this by looking at the development of the discharge during the first few pulses after ignition. Finally, a dielectric surface close to the streamer path can have a large influence on both the electric field distribution, as well as the electron density distribution and thereby can lead to specific paths that the streamer follows or avoids.

Contributed Papers

9:00

JW3 2 Screening in humid air plasmas* ANATOLY FILIPPOV, *SRC RF Troitsk Institute for Innovation and Fusion Research, 142190 Troitsk, Moscow, Russia* IVAN DERBENEV, *School of Chemistry, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom* NIKOLAY DYATKO, SERGEY KURKIN, *SRC RF Troitsk Institute for Innovation and Fusion Research, 142190 Troitsk, Moscow, Russia* Low temperature air plasmas containing H_2O molecules are of high importance for atmospheric phenomena, climate control, biomedical applications, surface processing, and purification of air and water. Humid air plasma created by an external ionization source is a good model of the troposphere where ions are produced by the galactic cosmic rays and decay products of air and soil radioactive elements such as Rn^{222}. The present paper is devoted to study the ionic composition and the screening in an ionized humid air at atmospheric pressure and room temperature. The ionization rate is varied in the range of $10^1 - 10^{18}$ $cm^{-3}s^{-1}$. The humid air with $0 - 1.5\%$ water admixture that corresponds to the relative humidity of $0 - 67\%$ at the air temperature equal to 20°C is considered. The ionic composition is determined on the analysis of more than a hundred processes. The system of 41 non-steady state particle number balance equations is solved using the 4th order Runge-Kutta method. The screening of dust particle charge in the ionized humid air are studied within the diffusion-drift approach. The screening constants are well approximated by the inverse Debye length and characteristic lengths of recombination and attachment processes.

*This work was supported by the Russian Science Foundation, Project No. 16-12-10424.

9:15

JW3 3 Gas flow phenomena in atmospheric-pressure plasma jets impinging on solid and liquid substrates investigated using numerical modelling and Schlieren imaging ADAM OBRUSNIK, *Department of Physical Electronics, Faculty of Science, Masaryk University, Brno, Czech Republic* MARCO BOSELLI, EMANUELE SIMONCELLI, AUGUSTO STANCAMPIANO, MATTEO GHERARDI, *Department of Industrial Engineering, Alma Mater Studiorum-Universitè di Bologna, Italy* LENKA ZAJICKOVA, *Department of Physical Electronics at Faculty of Science / Plasma Technologies at CEITEC, Masaryk University, Brno, Czech Republic* VITTORIO COLOMBO, *Department of Industrial Engineering, Alma Mater Studiorum-Universitè di Bologna, Italy* Neutral gas dynamics, i.e. the gas flow, gas mixing and heat transfer, play an important role in medical and other applications of helium atmospheric-pressure plasma jets (APPJs), as they determine the transport of plasma-generated active species to the substrate that is being treated. To capture the full complexity of this problem numerically, the buoyant Navier-Stokes equations (either laminar or with an appropriate turbulence model) must be solved together with multicomponent diffusion equations and the heat equation. In this contribution, we present the results of a combined experimental-numerical approach. The gas flow in three different plasma sources impinging on a flat surface, solid or liquid, is captured using high-speed Schlieren imaging. Special attention was dedicated to the onset of turbulence and the changes in the flow behaviour when a liquid substrate is used. By combining the experiments with numerical simulations of the flow (laminar and large-eddy simulation turbulent model), we analyze the role of three different types of plasmas on the gas flow and identify the phenomena that are likely responsible for the changes observed.

9:30

JW3 4 Cooling and Laser-Induced Fluorescence of Electronically-Excited He_2 in a Supersonic Microcavity Plasma Jet RUI SU, ANDREY MIRONOV, THOMAS HOULAHAN, JR., J. GARY EDEN, *University of Illinois at Urbana-Champaign* LABORATORY FOR OPTICAL PHYSICS AND ENGINEERING TEAM Laser-induced fluorescence (LIF) resulting from transitions between different electronic states of helium dimers generated within a microcavity plasma jet was studied with rotational resolution. In particular, the $d^3\Sigma_u^+$, $e^3\Pi_g$ and $f^3\Sigma_u^+$ states, all having electronic energies above 24 eV, are populated by a microplasma in 4 bar of helium gas and rotationally cooled through supersonic expansion. Analysis of two dimensional maps (spectrograms) of dimer emission spectra as a function of distance from the nozzle orifice indicates collisional coupling during the expansion between the lowest rotational levels of the $e^3\Pi_g$, $f^3\Sigma_u^+$ states and high rotational levels (around N=11) of the $d^3\Sigma_u^+$ state (all of which are in the $v = 0$ vibrational state). In an attempt to verify the coupling, a scanning dye laser (centered near 596 nm) pumps the $b^3\Pi_g \rightarrow f^3\Sigma_u^+$ transition of the molecule several hundred micrometers downstream of the nozzle. As a result, the emission intensities of relevant rotational lines are observed to be enhanced. This research shows the potential of utilizing microcavity plasma jets as a tool to study and manipulate the collisional dynamics of highly-excited diatomic molecules.

9:45

JW3 5 Characterization of atmospheric nanosecond discharge under highly inhomogeneous and transient electric field in air/water mixture KARIM OUARAS, PIERRE TARDIVEAU, LIONEL MAGNE, PASCAL JEANNEY, BLANDINE BOURNONVILLE, *Laboratoire de Physique des Gaz et des Plasmas, CNRS (UMR8578), Université Paris-Sud, Bât. 210, 91405 Orsay Cedex, France* We report the studies of a centimeter range pin-to-plane nanosecond repetitively discharge (<30 ns and 10 Hz) in standard conditions of pressure and temperature under very high positive voltage pulses (20 to 100 kV). In these typical conditions, plasma exhibit unusual diffuse and large structure. This kind of discharge is not well understood and in first approach, it requires (i) a description of plasma dynamic and (ii) behavior under relevant context (environmental issues . . .) using pertinent gas (humid air). Thus, we will first present sub-nanosecond imaging of the discharge obtained for typical conditions of stabilized plasma. Then we will focus on determination of rotational and vibrational temperature (OES) and preliminary results concerning the production and evolution of OH radical in temporal post-discharge in air/water mixture (PLIF). Theses spectroscopic measurements are undertaken as function of most influent parameters, *i.e.* voltage pulses features (amplitude, rise time and length) and water concentration.

SESSION JW4: PLASMA PROPULSION AND AEROSPACE APPLICATIONS II
Wednesday Morning, 12 October 2016
Room: 3 at 8:30

Contributed Papers

8:30

JW4 1 Plume properties measurement of an Electron Cyclotron Resonance Accelerator SARA CORREYERO, THEO VIALIS, JULIEN JARRIGE, DENIS PACKAN, *ONERA* Some emergent technologies for Electric Propulsion, such as the Electron Cyclotron Resonance Accelerator (ECRA), include magnetic nozzles to guide and expand the plasma. The advantages of this concept are well known: wall-plasma contact is avoided, it provides a current-free plume, it can allow to control thrust by modifying the magnetic field geometry, etc. However, their industrial application requires the understanding of the physical mechanisms involved, such as the electron thermodynamics at the plasma plume expansion, which is crucial to determine propulsive performances. This work presents a detailed characterization of the plasma plume axial profile in an ECR plasma thruster developed at ONERA. Langmuir, emissive, Faraday and ion energy probes are used to measure the electric potential space evolution, the current and electron energy distribution function in the plume, from the near field to the far field. The experimental results are compared with a quasi-1D (paraxial) steady-state kinetic model of a quasineutral collisionless magnetized plasma which is able to determine consistently the axial evolution of the electric potential and the electron and ion distribution functions with their associated properties.

8:45

JW4 2 A Coupled MHD and Thermal Model Including Electrostatic Sheath for Magnetoplasmadynamic Thruster Simulation* AKIRA KAWASAKI, KENICHI KUBOTA, IKKOH FUNAKI, *Japan Aerospace Exploration Agency* YOSHIHIRO OKUNO, *Tokyo Institute of Technology* Steady-state and self-field magnetoplasmadynamic (MPD) thruster, which utilizes high-intensity direct-current (DC) discharge, is one of the prospective candidates of future high-power electric propulsion devices. In order to accurately assess the thrust performance and the electrode temperature, input electric power and wall heat flux must correctly be evaluated where electrostatic sheaths formed in close proximity of the electrodes affect these quantities. Conventional model simulates only plasma flows occurring in MPD thrusters with the absence of electrostatic sheath consideration. Therefore, this study extends the conventional model to a coupled magnetohydrodynamic (MHD) and thermal model by incorporating the phenomena relevant to the electrostatic sheaths. The sheaths are implemented as boundary condition of the MHD model on the walls. This model simulated the operation of the 100-kW-class thruster at discharge current ranging from 6 to 10 kA with argon propellant. The extended model reproduced the discharge voltages and wall heat load which are consistent with past experimental results. In addition, the simulation results indicated that cathode sheath voltages account for approximately 5–7 V subject to approximately 20 V of discharge voltages applied between the electrodes.

*This work was supported by JSPS KAKENHI Grant Numbers 26289328 and 15J10821.

9:00

JW4 3 Characterization of an electrodeless ECR plasma thruster THÉO VIALIS, JULIEN JARRIGE, DENIS PACKAN, *ONERA - The French Aerospace Lab, 91120 Palaiseau, France* Several advanced plasma thruster technologies are currently being studied for the 1-10 mN range. ONERA is developing an Electron Cyclotron Resonance (ECR) plasma thruster, whose main advantage is to produce a current-free plume. It does not need a neutralizing cathode, which is one of the most fragile component in electrostatic thrusters. The ECR thruster consists of a coaxial structure immersed in an axial divergent magnetic field, fed with xenon. A plasma is generated by resonant absorption of microwave power (at 2.45 GHz) and is accelerated in an electron driven magnetic nozzle to produce the thrust. Previous measurements, performed with electrostatic probes, have shown promising performances. Electrons are heated at very high temperatures (several tens of eV), and ion kinetic energy is up to 400 eV in the plume. The estimated thrust is 1 mN, with an efficiency of 16%, for a power of 30W. In this work, a new version of the device has been conceived for direct thrust measurement on a dedicated thrust balance. The effect of magnetic field topology, propellant, mass flow rate and absorbed power are investigated. Thrust measurement are compared with values estimated from electrostatic probes results (ion current and energy).

9:15

JW4 4 Theory for the anomalous electron transport in Hall-effect thrusters* TREVOR LAFLEUR, *LPP Ecole Polytechnique, and Centre National d'Etudes Spatiale (CNES)* SCOTT BAALRUD, *Department of Physics and Astronomy, University of Iowa* PASCAL CHABERT, *LPP Ecole Polytechnique* Using insights from particle-in-cell (PIC) simulations, we develop a kinetic theory to explain the anomalous cross-field electron transport in Hall-effect thrusters (HETs). The large axial electric field in the acceleration region of HETs, together with the radially applied magnetic field, causes electrons to drift in the azimuthal direction with a very high velocity. This drives an electron cyclotron instability that produces large amplitude oscillations in the plasma density and azimuthal electric field, and which is convected downstream due to the large axial ion drift velocity. The frequency and wavelength of the instability are of the order of 5 MHz and 1 mm respectively, while the electric field amplitude can be of a similar magnitude to axial electric field itself. The instability leads to enhanced electron scattering many orders of magnitude higher than that from standard electron-neutral or electron-ion Coulomb collisions, and gives electron mobilities in good agreement with experiment. Since the instability is a strong function of almost all plasma properties, the mobility cannot in general be fitted with simple 1/B or $1/B^2$ scaling laws, and changes to the secondary electron emission coefficient of the HET channel walls are expected to play a role in the evolution of the instability.

*This work received financial support from a CNES postdoctoral research award.

SESSION KW1: THE WILL ALLIS PRIZE FOR THE STUDY OF IONIZED GASES
Wednesday Morning, 12 October 2016; Room: 1 at 10:30; Bill Graham, Queen's University, presiding

Invited Papers

10:30

KW1 1 Will Allis Prize for the Study of Ionized Gases: Electron Collisions – Experiment, Theory, and Applications*
KLAUS BARTSCHAT, *Drake University*

Electron collisions with atoms, ions, and molecules represent one of the very early topics of quantum mechanics. In spite of the field's maturity, a number of recent developments in detector technology (e.g., the "reaction microscope" or the "magnetic-angle changer") and the rapid increase in computational resources have resulted in significant progress in the measurement, understanding, and theoretical/computational description of few-body Coulomb problems. Close collaborations between experimentalists and theorists worldwide continue to produce high-quality benchmark data, which allow for thoroughly testing and further developing a variety of theoretical approaches. As a result, it has now become possible to reliably calculate the vast amount of atomic data needed for detailed modelling of the physics and chemistry of planetary atmospheres, the interpretation of astrophysical data, optimizing the energy transport in reactive plasmas, and many other topics – including light-driven processes, in which electrons are produced by continuous or short-pulse ultra-intense electromagnetic radiation. I will highlight some of the recent developments that have had a major impact on the field. This will be followed by showcasing examples, in which accurate electron collision data enabled applications in fields beyond traditional AMO physics. Finally, open problems and challenges for the future will be outlined.

*I am very grateful for fruitful scientific collaborations with many colleagues, and the long-term financial support by the NSF through the Theoretical AMO and Computational Physics programs, as well as supercomputer resources through TeraGrid and XSEDE.

SESSION MW6: POSTER SESSION II
Wednesday Evening, 12 October 2016
Exhibit Foyer at 17:30

MW6 1 ATOMIC AND MOLECULAR PROCESSES

MW6 2 Negative ion formation in potassium-adenine collisions T. CHUNHA, M MENDES, F FERREIRA DA SILVA, *Univ Nova de Lisboa* G GARCÍA, P LIMÁO VIEIRA We have devoted experimental studies to time-of-flight negative ion formation in electron transfer experiments from neutral potassium atoms with neutral adenine molecules[1]. Total partial cross sections have been obtained as a function of the collision energy, together with branching ratios for the most relevant fragment anions. Additional set of measurements in adenine derivatives have been performed in order to probe the role of negative ions as well as to probe whether site- and bond-selective excision is also a prevalent mechanism within electron transfer in atom-molecule collision experiments.

MW6 3 Electron cross-sections and transport in liquids and biomolecules RONALD WHITE, M. CASEY, D. COCKS, D. KONVALOV, *James Cook University* M. J. BRUNGER, *Flinders University* G. GARCIA, *CSIC* Z. PETROVIC, *Institute of Physics, Belgrade, Serbia* R. MCEACHRAN, S.J. BUCKMAN, *Australian National University* J. DE URQUIJO, *Universidad Nacional Autónoma de México* Modelling of electron induced processes in plasma medicine and radiation damage is reliant on accurate self-consistent sets of cross-sections for electrons in tissue. These cross-sections (and associated transport theory) must accurately account not only the electron-biomolecule interactions but also for the soft-condensed nature of tissue. In this presentation, we report on recent swarm experiments for electrons in gaseous water and tetrahydrofuran using the pulsed-Townsend experiment, and the associated development of self-consistent cross-section sets that arise from them. We also report on the necessary modifications to gas-phase cross-sections required to accurately treat electron transport in liquids. These modifications involve the treatment of coherent scattering and screening of the electron interaction potential as well as the development of a new transport theory to accommodate these cross-sections. The accuracy of the ab-initio cross-sections is highlighted through comparison of theory and experiment for electrons in liquid argon and xenon.

MW6 4 QDB: Validated Plasma Chemistries Database SARA RAHIMI, *Quantemol Ltd* JAMES HAMILTON, CHRISTIAN HILL, JONATHAN TENNYSON, *University College London* UCL TEAM One of most challenging recurring problems when modelling plasmas is the lack of data. This lack of complete and validated datasets hinders research on plasma processes and curbs development of industrial Applications [1]. We will describe the QDB project which aims to fill this missing link by provide a platform for exchange and validation of chemistry datasets. The database will collate published data on both electron scattering and heavy particle reactions and also facilitates and encourages peer-to-peer data sharing by its users. This data platform is rigorously supported by the validation methodical validation of the datasetsan automated chemistry generator employed; this methodology identifies missing reactions in chemistries which although important are currently unreported in the literature and employs mathematical methods to analyze the importance of these chemistries. Gaps in the datasets are filled using in house theoretical methods.

[1] J. Kushner and K. Bartschat, Proc. Nat. Acad. Sci. (2016) (In press).

MW6 5 COLLISIONS

MW6 6 Electron-impact excitation and ionization of boron* KEDONG WANG, *Henan Normal University* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* We present a comprehensive study of electron collisions with neutral boron atoms [1]. The calculations were performed with the B-Spline R-matrix (close-coupling) method [2], by employing a parallelized version of the associated computer code [3]. Elastic, momentum-transfer, excitation, and ionization cross sections were obtained for all transitions involving the lowest 11 states of boron, for incident electron energies ranging from threshold to 100 eV. A multi-configuration Hartree-Fock method with non-orthogonal term-dependent orbitals was used to generate accurate wavefunctions for the target states. Close-coupling expansions including 13, 51, and 999 physical and pseudo-states were set up to check the sensitivity of the predictions to variations in the theoretical model. The cross-section dataset generated in this work is expected to be the most accurate one available today and should be sufficiently comprehensive for most modeling applications involving neutral boron.

*Work supported by the China Scholarship Council and the United States National Science Foundation under grants PHY-1403245 and PHY-1520970, and by the XSEDE allocation PHY-090031.

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[2]O. Zatsarinny and K. Bartschat, J. Phys. B **46**, 112001 (2013).
[3]O. Zatsarinny, Comp. Phys. Commun. **174**, 273 (2006).

MW6 7 Vibrational excitation and vibrationally resolved electronic excitation cross sections of positron-H_2 scattering* MARK ZAMMIT, *Theoretical Division, Los Alamos National Laboratory* DMITRY FURSA, JEREMY SAVAGE, IGOR BRAY, *Curtin University* Vibrational excitation and vibrationally resolved electronic excitation cross sections of positron-H_2 scattering have been calculated using the single-centre molecular convergent close-coupling (CCC) method. The adiabatic-nuclei approximation was utilized to model the above scattering processes and obtain the vibrationally resolved positron-H_2 scattering length. As previously demonstrated [1], the CCC results are converged and accurately account for virtual and physical positronium formation by coupling basis functions with large orbital angular momentum. Here vibrationally resolved integrated and differential cross sections are presented over a wide energy range and compared with previous calculations and available experiments.

*Los Alamos National Laboratory and Curtin University.

[1]M. C. Zammit *et al.*, J. Phys. Conf. Ser. **635**, 012009 (2015).

MW6 8 CCC calculated differential cross sections of electron-H_2 scattering* DMITRY FURSA, *Curtin University* MARK ZAMMIT, *Los Alamos National Laboratory* JEREMY SAVAGE, IGOR BRAY, *Curtin University* Recently we applied the molecular convergent close-coupling (CCC) method to electron scattering from molecular hydrogen H_2 [1]. Convergence of the major differential cross sections has been explicitly demonstrated in the fixed-nuclei approximation. A large close-coupling expansion that coupled highly excited states and ionization channels proved to be important to obtain convergent results. Here we present benchmark elastic and electronic excitation differential cross sections for $b^3\Sigma_u^+$, $a^3\Sigma_g^+$, $c^3\Pi_u$, $B^1\Sigma_u^+$, $EF^1\Sigma_g^+$, $C^1\Pi_u$, and $e^3\Sigma_u^+$ states and compare with available experiment and previous calculations.

*Work supported by Los Alamos National Laboratory and Curtin University.

[1]M. C. Zammit *et al.*, Phys. Rev. Lett. accepted (2016).

MW6 9 Elastic Electron Scattering from Hexafluoropropene* LEIGH HARGREAVES, AHMED SAKAAMINI, BORNA HLOUSEK, SABAHA KHAKOO, MURTADHA KHAKOO, *Cal State University Fullerton, USA* CARL WINSTEAD, VINCENT MCKOY, *Caltech, USA* Low energy, experimental and theoretical elastic electron scattering differential cross sections (DCS) are presented. The experimental DCSs are obtained at incident electron energies from 0.5eV to 20eV and for scattering angles from 10 to 130 degrees using the relative flow method with helium as a reference standard. Our model uses the multi-channel Schwinger method with polarization effects included.

*Supported by the NSF DAMOP.

MW6 10 Study of inelastic e-Cd and e-Zn collisions MARIUSZ PIWINSKI, LUKASZ KLOSOWSKI, DAREK DZICZEK, STANISLAW CHWIROT, *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Torun, Grudziadzka 5, 87-100 Torun, Poland* Electron-photon coincidence experiments are well known for providing more detailed information about electron-atom collision than any other technique [1-3]. The Electron Impact Coherence Parameters (EICP) values obtained in such studies deliver the most complete characterization of the inelastic collision and allow for a verification of proposed theoretical models [4]. We present the results of Stokes and EICP parameters characterising electronic excitation of the lowest singlet P-state of cadmium and zinc atoms for various collision energies [5-7]. The experiments were performed using electron-photon coincidence technique in the coherence analysis version. The obtained data are presented and compared with existing CCC [8] and RDWA [9] theoretical predictions.

[1]D. Dyl *et al.*, J. Phys. B: At. Mol. Opt. Phys. **32**, 837 (1999).
[2]M. Piwinski *et al.*, J. Phys. B: At. Mol. Opt. Phys. **39**, 1945 (2006).
[3]L. Klosowski *et al.*, Phys. Rev. A **80**, 062709 (2009).
[4]N. Andersen *et al.*, Phys. Rep. **165**, 1 (1988).
[5]M. Piwinski *et al.*, J. Phys. B: At. Mol. Opt. Phys. **35**, 3821 (2002).
[6]M. Piwinski *et al.*, Phys. Rev. A **86**, 052706 (2012).
[7]M. Piwinski *et al.*, Phys. Rev. A **91**, 062704 (2015).
[8]M. Berrington *et al.*, Phys. Rev. A **85**, 042708 (2012).
[9]T. Das *et al.*, Phys. Lett. A **378**, 641 (2014).

MW6 11 Efficient thermoelectric trap for metal vapours suitable for high-vacuum system MARIUSZ PIWINSKI, LUKASZ KLOSOWSKI, DAREK DZICZEK, STANISLAW CHWIROT, *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Torun, Grudziadzka 5, 87-100 Torun, Poland* Atomic beams are widely used in various collisional experiments [1-3]. Typically, cold traps are used to prevent the investigated atoms from spreading within the vacuum chamber and contaminating the system. Usually such a trap consists of a vacuum feedthrough with metal element cooled with liquid nitrogen or dry ice on the atmosphere side and a metal trap in the vacuum [4]. Using liquid nitrogen or dry ice is relatively inconvenient due to high costs of operation and a need of periodically refilling the reservoir of the cold medium. We present a new thermoelectric cold trap composed of water–cooled vacuum feedthrough with Peltier modules placed at the high vacuum end. The present system ensures the cold trap temperature below −20°C, low enough to efficiently catch the atoms of interest. The new cold trap was characterised and compared with typical LN_2 trap [2,5].

[1]S. Napier *et al.*, Phys. Rev. A **79**, 042702 (2009).
[2]M. Piwinski *et al.*, Phys. Rev. A **91**, 062704 (2015).
[3]B. P. Marinkovic *et al.*, Rad. Phys. and Chem. **76**, 455 (2007).
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[5]M. Piwinski *et al.*, J. Phys. B: At. Mol. Opt. Phys. **35**, 3821 (2002).

MW6 12 Coulomb crystal as a detector in electron impact ionization experiment LUKASZ KLOSOWSKI, MARIUSZ PIWINSKI, SZYMON WOJTEWICZ, DANIEL LISAK, DAREK DZICZEK, STANISLAW CHWIROT, *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Torun, Grudziadzka 5, 87-100 Torun, Poland* Ensembles of ions in trap at sufficiently low temperature can form a structure called Coulomb crystal. Some species of such ions can be optically cooled and observed using CCD camera. Number of ions composing the crystal can be determined with high accuracy. Other, invisible species of ions can be sympathetically cooled and detected indirectly by observation of their influence on visible ones. Thus, the efficiency of ionization processes leading to Coulomb crystal formation can be determined. We present preliminary results for electron-impact-ionized molecules forming a multi-species Coulomb crystal in a linear segmented Paul trap together with atomic calcium ions.

MW6 13 Calculations of non-coplanar ionization of helium ALLAN STAUFFER, *York University, Toronto* TIMJAN KALAJDZIEVSKI, *York University, Toronto, Canada* Nixon *et al.* [1] have measured the triple differential cross sections for electron ionization of the noble gases in the case where the direction of the incident electron is perpendicular to the plane containing the outgoing electrons which have equal energies. Miller *et al.* [2] have carried out non-relativistic distorted-wave Born approximation calculations in these cases. In preparation for a study of all of these cases we have carried out calculations of the ionization of helium using a relativistic distorted-wave model. The evaluation of the relativistic distorted waves representing the outgoing electrons is based on a program [3] which produces relativistic coulomb waves which has been modified to take account of the finite size of the helium nucleus. The calculations are based on an integral equation approach as given in [4] and an asymptotic correction has been applied to account for the integration over an infinite interval. Convergence in the sum over partial waves has been obtained and a preliminary evaluation of the explicit inclusion of post-collision interaction has been carried out.

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MW6 14 A non-iterative treatment of the non-local exchange terms in the Complex Optical Potential method ALLAN STAUFFER, *York University* ROBERT MCEACHRAN, *Australian National University* Non-local exchange terms in atomic scattering equations are usually treated iteratively. This method normally works well but there can be problems with convergence, either requiring a large number of iterations or converging to a spurious value. It has long been known [1] that these terms can be treated non-iteratively but at the cost of expanding the number of equations needed to be solved. With the vastly increased memory and speed of modern computers, this approach is now feasible even for heavier targets. We have decided to implement this method in our calculations of electron elastic scattering from atoms using the Complex Optical Potential (COP) method [2] which is based on the relativistic Dirac equations. This method accounts for incident flux lost to the elastic channels through inelastic processes (excitation and ionization) via the imaginary part of the optical potential and also provides a value for the total cross section for these processes. The basis for the method will be given along with sample calculations where the iterative method fails.

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[2]S. Chen, R. P. McEachran, and A. D. Stauffer, J. Phys. B: At. Mol. Opt. Phys. **41**, 025201 (2008).

MW6 15 An out-of-plane $(e, 2e)$ study of He autoionization from 80 to 488 eV incident energies* B.A. DEHARAK, *Illinois Wesleyan University* B.N. KIM, C.M. WEAVER, *University of Kentucky* K. BARTSCHAT, *Drake University* N.L.S. MARTIN, *University of Kentucky* We report out-of-scattering-plane $(e, 2e)$ measurements on helium $2\ell 2\ell'$ autoionizing levels for 80, 120, 150, and 488eV incident electron energies, and scattering angles 60°, 45°, 39.2°, and 20.5°, respectively. The kinematics are the same in all cases: ejected electrons are detected in a plane that contains the momentum transfer direction and is perpendicular to the scattering plane, and the momentum transfer is 2.1 a.u.. The 80eV results complete our sets of measurements at low, intermediate [1], and high [2], incident energies. The results are presented as $(e, 2e)$ angular distributions energy-integrated over each level, and are compared with our theory calculated for 488eV incident electron energy. The 120eV, 150eV and 488eV experiments are characterized by recoil peaks appropriate to each autoionizing level. However, for the 80eV angular distributions, these recoil peaks are largely absent for all levels, including the ^3P level observed at this energy.

*This work was supported by the National Science Foundation under grants Nos. PHY-0855040 (NLSM), PHY-1402899 (BAd), and PHY-1212450 (KB).

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MW6 16 Convoluted Quasi Sturmian basis for the two-electron continuum LORENZO UGO ANCARANI, *Universite de Lorraine* A S ZAYTSEV, S A ZAYTSEV, *Pacific National University, Khabarovsk, Russia* In the construction of solutions for the Coulomb three-body scattering problem one encounters a series of mathematical and numerical difficulties, one of which are the cumbersome boundary conditions the wave function should obey. We propose to describe a Coulomb three-body system continuum with a set of two-particle functions, named Convoluted Quasi Sturmian (CQS) in [1]. They are built using recently introduced Quasi Sturmian (QS) functions [2] which have the merit of possessing a closed form. Unlike a simple product of two one-particle functions, by construction, the CQS functions look asymptotically like a six-dimensional outgoing spherical wave. The proposed CQS basis is tested through the study of the double ionization of helium by high-energy electron impact in the framework of the Temkin-Poet model [3]. An adequate logarithmic-like phase factor is further included in order to take into account the Coulomb interelectronic interaction and formally build the correct asymptotic behavior when all interparticle distances are large. With such a phase-factor (that can be easily extended to take into account higher partial waves) rapid convergence of the expansion can be obtained.

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[3]G. Gasaneo *et al.*, Phys. Rev. A **87**, 042707 (2013).

MW6 17 Electron impact ionization–excitation of Helium LORENZO UGO ANCARANI, *Universite de Lorraine* A I GOMEZ, *IAFE, Buenos Aires* G GASANEO, *Universidad Nacional del Sur, Bahia Blanca* D M MITNIK, *IAFE, Buenos Aires* M J AMBROSIO, *Kansas State University* We calculate triple differential cross sections (TDCS) for the process of ionization–excitation of Helium by fast electron impact in which the residual ion is left in the n=2 excited state. We chose the strongly asymmetric kinematics used in the experiment performed by Dupré *et al.* [1]. In a perturbative scheme, for high projectile energies the four–body problem reduces to a three–body one [2] and, within that framework, we solve the time- independent Schrödinger equation with a Sturmian approach [3]. The method, based on Generalized Sturmian Functions (GSF), is employed to obtain the initial ground state of Helium, the single-continuum state and the scattering wave function; for each of them, the GSF basis is constructed with the corresponding adequate asymptotic conditions. Besides, the method presents the following advantage: the scattering amplitudes can be extracted directly in the asymptotic region of the scattering solution, and thus the TDCS can be obtained without requiring a matrix element evaluation.

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MW6 18 Ionization of small molecules by electron impact: a Sturmian approach* LORENZO UGO ANCARANI, CARLOS GRANADOS, *Universite de Lorraine* The Sturmian approach [1], using Generalized Sturmian Functions (GSF), has been applied successfully to study (e,3e) and (γ,2e) processes in helium. A first extension of the method to molecular systems has been developed for the study of single photoionization [2,3]. In this contribution, we use the tool to look at ionization by electron impact of small molecules. In particular, we are interested in (e,2e) processes on CH_4, NH_3 and H_2O under sufficiently asymmetrical kinematical conditions as to ignore exchange between the two escaping electrons. Within a single active electron approximation, we solve the time-independent, first-order perturbative, Schrödinger equation, expanding the scattering wave function in a GSFs basis set. The adequate asymptotic behavior of all basis elements allows us to extract the transition amplitudes directly from the expansion coefficients, without requiring any evaluation of a matrix element. From the amplitudes, we calculate triply differential cross sections (TDCSs) and compare them with theoretical and relative experimental data.

*We acknowledge the CNRS (PICS Project No. 06304) for funding.

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[2]C. M. Granados–Castro *et al.*, Adv. Quantum Chem. **73**, 3 (2016).
[3]C. M. Granados-Castro, Ph. D. thesis, Université de Lorraine, Metz (2016).

MW6 19 Double ionization of helium by impact of fast protons LORENZO UGO ANCARANI, *Universite de Lorraine* E L GAGGIOLI, *IAFE, Buenos Aires* M J AMBROSIO, *Kansas State University* D M MITNIK, *IAFE, Buenos Aires* G GASANEO, *Universidad Nacional del Sur, Bahia Blanca* In comparison with the electron impact case, fully differential cross sections for the double ionization of helium by proton impact have been little investigated. The reasons are quite simple: experimentally, the measurement requires a long time as the count rates are very low; theoretically, the full four-body problem poses a formidable challenge. The present theoretical investigation is a contribution towards understanding this process. We performed [1] ab initio first Born calculations for proton impinging with 6 MeV, in the experimental configuration investigated in [2]. We solve a three-body scattering driven equation with the Generalized Sturmian Functions method [3]. Using the asymptotic behavior of the solution, we extract directly the transition matrix and thus the corresponding fully differential cross section. A detailed comparison with the relative experimental data will be presented at the conference.

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[2]D. Fischer *et al.*, Phys. Rev. Lett. **90**, 243201 (2003).
[3]G. Gasaneo *et al.*, Adv. Quantum Chem. **57**, 153 (2013).

MW6 20 Single- and two-center interference effects in fully differential cross sections for dissociative capture in 75 keV p H_2 collisions* MICHAEL SCHULZ, BASU LAMICHHANE, THUSITHA ARTHANAYAKA, *Missouri Univ of Sci & Tech* AHMAD HASAN, *uae university* JUAN REMOLINA, SHEN LI, *Missouri Univ of Sci & Tech* We have measured fully differential cross sections (FDCS) for dissociative capture in 75 keV p + H_2 collisions for coherent and incoherent projectiles. Data were obtained for a kinetic energy release of 1 eV, so that only vibrational excitation in the H_2^+ ion contributes to dissociation. The FDCS were analyzed for various molecular orientations (relative to the transverse momentum transfer direction q_x) as a function of the scattering angle. In the ratio between the coherent and incoherent FDCS for a molecular orientation perpendicular to q_x a structure was observed, which is due to single-center interference. For a parallel orientation a structure of different shape is observed, which is due to a combination of single- and two-center interference. Furthermore, the data provide an additional independent confirmation that differences between coherent and incoherent cross sections are not merely due to the experimental resolution.

*Work supported by NSF under Grant No. PHY-1401586.

MW6 21 X-ray emission in charge-exchange ion-atom and ion-molecule collisions* ANTHONY C.K. LEUNG, TOM KIRCHNER, *York University* Charge exchange between highly-charged ions in solar winds and cometary neutrals is the primary process in many observed radiation phenomena in astrophysical environments. The present work examines this process using the two-center basis generator method within the independent electron model. We consider single capture in C^{6+}-He collisions from low to intermediate impact energies and benchmark our results with measurements by Defay *et al.* [1,2]. We also consider single and multiple capture in O^{6+}-Ar collisions, where impact energies more closely resemble solar wind speeds (approximately from 1.17 to 2.33 keV/u). These results are compared with measurements and calculations by Machacek *et al.* [3]. An outlook on collision-induced radiative processes involving ion-molecule collision systems will be given as well.

*Work supported by SHARCNET, OGS, and NSERC, Canada.

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[3]J. R. Machacek *et al.*, Astrophys. J. **809**, 75 (2015).

MW6 22 Fragmentation of methane molecules by antiproton impact* ARASH SALEHZADEH, TOM KIRCHNER, *York University* Extending previous work for proton impact [1], we have investigated the fragmentation of methane molecules due to collisions with antiprotons in the 25 keV to 5 MeV impact energy range. The multi-center nature of the problem is addressed by using a spectral representation of the molecular Hartree-Fock-level Hamiltonian and a single-center expansion of the initially populated molecular orbitals. The two-center basis generator method (TC-BGM) is used for orbital propagation. Electron-removal cross sections obtained from the TC-BGM solutions are complemented with a dynamical decay-route fragmentation model [2] to calculate cross sections for the production of fragment ions. Good agreement with the available experimental data [3] is observed for CH_4^+, CH_3^+, CH_2^+ and CH^+.

*Work supported by NSERC, Canada.

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MW6 23 Spin-density functional theory treatment of He^+-He collisions* MATTHEW BAXTER, TOM KIRCHNER, *York University* EBERHARD ENGEL, *Goethe University Frankfurt* The He^+-He collision system presents an interesting challenge to theory. On one hand, a full treatment of the three-electron dynamics constitutes a massive computational problem that has not been attempted yet; on the other hand, simplified independent-particle-model based descriptions may only provide partial information on either the transitions of the initial target electrons or on the transitions of the projectile electron, depending on the choice of atomic model potentials. We address the He^+-He system within the spin-density functional theory framework on the exchange-only level. The Krieger-Li-Iafrate (KLI) approximation is used to calculate the exchange potentials for the spin-up and spin-down electrons, which ensures the correct asymptotic behavior of the effective (Kohn-Sham) potential consisting of exchange, Hartree and nuclear Coulomb potentials. The orbitals are propagated with the two-center basis generator method. In each time step, simplified versions of them are fed into the KLI equations to calculate the Kohn-Sham potential, which, in turn, is used to generate the orbitals in the next time step. First results for the transitions of all electrons and the resulting charge-changing total cross sections will be presented at the conference.

*Work supported by NSERC, Canada.

MW6 24 An independent atom model description of ion-molecule collisions including geometric screening corrections: application to biomolecules* H. J. LÜDDE, A. ACHENBACH, T. KALKBRENNER, H.C. JANKOWIAK, *Goethe University Frankfurt* T. KIRCHNER, *York University* Recently, we proposed to calculate electron removal cross sections for ion-molecule collisions in an independent atom model that accounts for geometric screening corrections [1]. The correction coefficients are obtained from using a pixel counting method (PCM) for the exact calculation of the effective cross sectional area that emerges when the molecular cross section is pictured as a structure of (overlapping) atomic cross sections. This structure varies with the relative orientation of the molecule with respect to the projectile beam direction and, accordingly, orientation-independent total cross sections are obtained from averaging the pixel count over many orientations. In this contribution, we apply the PCM to proton collisions from amino acids and DNA and RNA nucleobases. The strength of the screening effect is analyzed by comparing the PCM results with Bragg additivity rule cross sections and with experimental data where available.

*Work supported by NSERC, Canada.

[1] H. J. Lüdde *et al.*, Eur. Phys. J. D **70**, 82 (2016).

MW6 25 Path Integral Approach to Atomic Collisions* ALLISON HARRIS, *Illinois State University* The Path Integral technique is an alternative formulation of quantum mechanics that is based on a Lagrangian approach. In its exact form, it is completely equivalent to the Hamiltonian-based Schrödinger equation approach. Developed by Feynman in the 1940's, following inspiration from Dirac, the path integral approach has been widely used in high energy physics, quantum field theory, and statistical mechanics. However, only in limited cases has the path integral approach been applied to quantum mechanical few-body scattering. We present a theoretical and computational development of the path integral method for use in the study of atomic collisions. Preliminary results are presented for some simple systems. Ultimately, this approach will be applied to few-body ion-atom collisions.

*Work supported by NSF grant PHY-1505217.

MW6 26 Determination of Collisional Quenching Rate Coefficient of $N_2(A^3\Sigma_u^+)$ by H_2O SUSUMU SUZUKI, HARUO ITOH, *Chiba Institute of Technology* The effective lifetimes of metastable excited molecule $N_2(A^3\Sigma_u^+)$ in N_2/10.2ppm H_2O and N_2/103ppm H_2O mixtures were measured by waveform analysis(1) of the transient ionization current after interruption of the initial electron from the cathode in the Townsend discharge region. The collisional quenching rate coefficient of $N_2(A^3\Sigma_u^+)$ by H_2O was determined together with the diffusion coefficient of $N_2(A^3\Sigma_u^+)$ in nitrogen and the reflection coefficient of $N_2(A^3\Sigma_u^+)$ at the cathode surface with the procedure based on the diffusion equation analysis(2). The obtained collisional quenching rate coefficient of $N_2(A^3\Sigma_u^+)$ by H_2O is 5.7×10^{-13} cm^3/s. This value is ten times as large of the value reported by Callear and Wood(3).

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[3] A. B. Callear and P. M. Wood, Trans. Faraday Soc. **67**, 598 (1971).

MW6 27 Excess Thermal Energy In The Cell Loaded With Mixture of Ni Powder And Li[AlH_4] SHI NGUYEN-KUOK,* YURY MALAKHOV,† IVAN KOROTKIKH,‡ *None* Interest has significantly increased in the study of Low-Energy Nuclear Reactions. Especially after the publication of the test results from Andrea Rossi's high-temperature heat source that operates on a mixture of Nickel powder and Lithium Aluminum Hydride. Initial experiments showed that the reaction is unstable; occurring in a narrow temperature range (in practice, it is outside the melting temperature of the fuel materials). In this work we describe the design of the heat generator, the calorimetric method for measuring the amount of heat energy. The results demonstrate excess heat during heating the powder mixture of Ni and Li[AlH_4] to temperatures ranging from 1030—1140 °C. The generator did not expose an X-ray photographic emulsion.

*Professor.
†Associate professor.
‡Student.

MW6 28 DISSOCIATION, RECOMBINATION AND ATTACHMENT

MW6 29 Ternary recombination of H_3^+, H_2D^+, HD_2^+, and D_3^+ with electrons in He/Ar/H_2/D_2 gas mixtures* ABEL KALOSI, PETR DOHNAL, RADEK PLASIL, *Charles University in Prague, Prague 18000, Czech Republic* RAINER JOHNSEN, *University of Pittsburgh, Pittsburgh, PA 15260, USA* JURAJ GLOSIK, *Charles University in Prague, Prague 18000, Czech Republic* The temperature dependence of the ternary recombination rate coefficients of H_2D^+ and HD_2^+ ions has been studied in the temperature range of 80–150 K at pressures from 500 to 1700 Pa in a stationary afterglow apparatus equipped with a cavity ring-down spectrometer. Neutral gas mixtures consisting of He/Ar/H_2/D_2 (with typical number densities $10^{17}/10^{14}/10^{14}/10^{14}$ cm^{-3}) were employed to produce the desired ionic species and their fractional abundances were monitored as a function of helium pressure and the $[D_2]/[H_2]$ ratio of the neutral gas. In addition, the translational and the rotational temperature and the ortho to para ratio were monitored for both H_2D^+ and HD_2^+ ions. A fairly strong pressure dependence of the effective recombination rate coefficient was observed for both ion species, leading to ternary recombination rate coefficients close to those previously found for (helium assisted) ternary recombination of H_3^+ and D_3^+ [1].

*Work supported by: Czech Science Foundation projects GACR 14-14649P, GACR 15-15077S, GACR P209/12/0233, and by Charles University in Prague Project Nr. GAUK 692214.

[1] R. Johnsen *et al.*, J. Phys. Chem. **117**, 9477 (2013).

MW6 30 Stationary-Afterglow measurements of dissociative recombination of H_2D^+ and HD_2^+ ions* PETR DOHNAL, ABEL KALOSI, RADEK PLASIL, *Charles University in Prague, Prague 18000, Czech Republic* RAINER JOHNSEN, *University of Pittsburgh, Pittsburgh, PA 15260, USA* JURAJ GLOSIK, *Charles University in Prague, Prague 18000, Czech Republic* Binary recombination rate coefficients of H_2D^+ and HD_2^+ ions have been measured at a temperature of 80 K in an afterglow plasma experiment in which the fractional abundances of H_3^+, H_2D^+, HD_2^+, and D_3^+ ions were varied by adjusting the $[D_2]/([D_2] + [H_2])$ ratio of the neutral gas. The fractional abundances of the four ion species during the afterglow and their rotational states were determined in situ by continuous-wave cavity ring-down absorption spectroscopy (CRDS), using overtone transitions from the ground vibrational states of the ions. The experimentally determined recombination rate coefficients will be compared to results of advanced theoretical calculations and to the known H_3^+ and D_3^+ recombination rate coefficients. We conclude that the recombination coefficients depend only weakly on the isotopic composition. Astrophysical implications of the measured recombination rate coefficients will be also discussed.

*Work supported by: Czech Science Foundation projects GACR 14-14649P, GACR 15-15077S, GACR P209/12/0233, and by Charles University in Prague Project Nr. GAUK 692214.

MW6 31 Computational Study on Dissociation Properties of C_4F_6 Molecules* HEECHOL CHOI, MI-YOUNG SONG, JUNG-SIK YOON, *Plasma Technology Research Center, National Fusion Research Institute* PLASMA FUNDAMENTAL TECHNOLOGY RESEARCH TEAM Saturated or unsaturated perfluorocarbons(PFCs) have been used extensively in dry etching processes due to their relatively low global warming potential and their high CF_2 radical levels in commercial plasma processes. Many experimental and theoretical studies of these species have been performed for useful information about physical and chemical properties of PFCs. Recently, it was reported that the ωB97X-D/aVTZ method is strongly recommended as the best practical density functional theory (DFT) for rigorous and extensive studies of PFCs because this theoretical level shows the high performance and reliability especially for van der Waals interactions. Among various PFCs, this study focuses on C_4F_6 molecules including c-C_4F_6, 1,3-C_4F_6, and 2-C_4F_6 isomers. All the feasible isomerization and dissociation paths of C_4F_6 molecules were investigated mainly at the ωB97X-D/aVTZ level. Their reaction rate constants were computed by using variational transition-state theory for a deep insight into C_4F_6's reaction mechanism. Fates and roles of C_4F_6 molecules and their fragments in plasma phases could be explained based on our theoretical results and data.

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

MW6 32 DISBRIBUTION FUNCTIONS AND TRANSPORT COEFFICIENTS FOR ELECTRONS AND IONS

MW6 33 Transport coefficients of He^+ ions in helium RAINER JOHNSEN, *University of Pittsburgh* LARRY VIEHLAND, *Chatham University* BENJAMIN GRAY, TIMOTHY WRIGHT, *University of Nottingham* New experimental mobilities of $^4He^+$ in ^{4}He at 298.7 K, as a function of E/N, have been determined. Uncertainties in the mobilities were reduced to about 1% by using a shuttered drift tube. Comparison with previously measured values show that only one set of previous data is reliable. We demonstrate that the mobilities and diffusion coeffcients of $^4He^+$ in ^{4}He can be calculated over wide ranges of E/N with high precision if accurate potential energy curves are available for the $X^2\Sigma_u^+$ and $A^2\Sigma_g^+$ states, and if one takes into account resonant charge transfer and corrects for quantum-mechanical effects. Potentials, obtained by extrapolation of results from d-aug-cc-pVXZ (X=6,7) basis sets using the CASSCF+MRCISD approach were found to be in exceptionally close agreement with the best potentials available (separately) and with experiment, and those were subsequently used in a new computer program to determine semi-classical phase shifts and transport cross sections, from which the gaseous ion transport coefficients are determined. A new set of data for the mobilities of alpha particles ($He^{2+)}$ ions was obtained as a byproduct of the experiment, but the transport theory has not yet been completed.

MW6 34 Transport Parameters For Positive IONS In Pure H_2O DC Discharge* ZORAN PETROVIC, VLADIMIR STOJANOVIC, *Inst of Physics., University of Belgrade, P.O.Box 68, 11080, Belgrade, Serbia* JASMINA JOVANOVIC, *Faculty of Mechanical Engieneering, University of Belgrade, Kraljice Marije 16, 11000 Belgrade, Serbia* DRAGANA MARIC, *Inst of Physics., University of Belgrade, P.O.Box 68, 11080, Belgrade, Serbia* Transport properties of positive ions originating from H_2O (H_2O^+, OH^+) in DC fields and at the room temperature were calculated by using Monte Carlo simulation technique. Initially, the relevant cross section sets were assessed by using Denpoh-Nanbu theory for resolving between elastic and reactive collision events and then resolving contribution of exothermic processes from available experimental data. Newest experimentally or theoretically determined cross sections were compiled and included wherever possible. We present transport coefficients for low and moderate reduced electric fields E/N (N-gas density) accounting for non-conservative processes.

*Acknowledgment to Ministry of Education, Science and Technology of Republic Serbia, Projects No. 171037 and 410011.

MW6 35 Third order transport coefficients for electrons and positrons in gases SASA DUJKO, ILIJA SIMONOVIC, *Institute of Physics, University of Belgrade, Serbia* RONALD WHITE, *College of Science, Technology & Engineering, James Cook University, Australia* ZORAN PETROVIC, *Institute of Physics, University of Belgrade, Serbia* Third order transport coefficients (the skewness tensor) of the electron and positron swarms, in atomic and molecular gases, are investigated. The knowledge of the skewness tensor is necessary for the conversion of the hydrodynamic transport coefficients to the arrival time and steady-state Townsend transport data as well as for the determination of the deviations of the spatial density profiles from an ideal Gaussian. In this work, we investigate the structure and symmetries along individual elements of the skewness tensor by the group projector method. Individual components of the skewness tensor are calculated using a Monte Carlo simulation technique and multi term theory for solving the Boltzmann equation. Results obtained by these two methods are in excellent agreement. We extend previous studies by considering the sensitivity of the skewness components to explicit and implicit effects of non-conservative collisions, post-ionization energy partitioning, and inelastic collisions. The errors of the two term approximation for solving the Boltzmann equation are highlighted. We also investigate the influence of a magnetic field on the skewness tensor in varying configurations of electric and magnetic fields. Among many interesting points, we have observed a strong correlation between the skewness and diffusion.

MW6 36 Transport properties of electrons and transition of an electron avalanche into a streamer in atomic liquids SASA DUJKO, ILIJA SIMONOVIC, *Institute of Physics, University of Belgrade, Serbia* GREGORY BOYLE, RONALD WHITE, *College of Science, Technology & Engineering, James Cook University, Australia* DANKO BOSNJAKOVIC, ZORAN PETROVIC, *Institute of Physics, University of Belgrade, Serbia* A Monte Carlo simulation technique is developed and used to calculate transport coefficients of electron swarms in non-polar atomic liquids. We employ the two model processes in which only momentum and energy are exchanged, respectively, to account for structure dependent coherent elastic scattering at low energies. The validity of the code is confirmed by comparison with results of previous authors. We apply two scenarios for higher energy cross sections. In the first scenario excitations in the liquid phase are approximated by excitations in the gas phase. In the second scenario excitations are completely neglected. Ionization threshold is reduced to values which are suggested in the literature, in both scenarios. Transport coefficients in these two scenarios, as well as transport coefficients for gas and liquid phases are compared. Special attention has been given to the structure induced negative differential conductivity (NDC), which has been observed both in this work, and in previous publications. Spatially-resolved electron transport properties are calculated in order to understand this phenomenon. The important aspect of this work is modeling of the transition of an electron avalanche into a streamer. Calculations are performed using 1D and 1.5D fluid models. Streamer properties in scenarios with and without excitations are compared.

MW6 37 Monte Carlo simulations of electron transport in strongly attaching gases ZORAN PETROVIC, JASMINA MIRIC, ILIJA SIMONOVIC, DANKO BOSNJAKOVIC, SASA DUJKO, *Institute of Physics, University of Belgrade, Serbia* Extensive loss of electrons in strongly attaching gases imposes significant difficulties in Monte Carlo simulations at low electric field strengths. In order to compensate for such losses, some kind of rescaling procedures must be used. In this work, we discuss two rescaling procedures for Monte Carlo simulations of electron transport in strongly attaching gases: (1) discrete rescaling, and (2) continuous rescaling. The discrete rescaling procedure is based on duplication of electrons randomly chosen from the remaining swarm at certain discrete time steps. The continuous rescaling procedure employs a dynamically defined fictitious ionization process with the constant collision frequency chosen to be equal to the attachment collision frequency. These procedures should not in any way modify the distribution function. Monte Carlo calculations of transport coefficients for electrons in SF_6 and CF_3I are performed in a wide range of electric field strengths. However, special emphasis is placed upon the analysis of transport phenomena in the limit of lower electric fields where the transport properties are strongly affected by electron attachment. Two important phenomena arise: (1) the reduction of the mean energy with increasing E/N for electrons in SF6, and (2) the occurrence of negative differential conductivity in the bulk drift velocity of electrons in both SF_6 and CF_3I.

MW6 38 Electron transport in mercury vapor: magnetic field effects, dimer induced NDC and multi-term analysis ZORAN PETROVIC, JASMINA MIRIC, ILIJA SIMONOVIC, SASA DUJKO, *Institute of Physics, University of Belgrade, Serbia* A multi term theory for solving the Boltzmann equation and Monte Carlo simulation technique are used to investigate electron transport in varying configurations of electric and magnetic fields in mercury vapor. Using different sets of cross sections for electron scattering in mercury as an input in our Boltzmann and Monte Carlo codes, we have calculated data for electron transport as a function of reduced electric and magnetic fields. A multitude of kinetic phenomena in electron transport has been observed and discussed using physical arguments. In particular, we discuss two important phenomena: (1) for certain values of electric and magnetic field, we find regions where swarm mean energy increases with increasing magnetic field for a fixed electric field, and (2) the occurrence of negative differential conductivity (NDC) for higher pressures and temperatures. In particular, NDC is induced by the presence of mercury dimers. The measured drift velocities agree very well with our Monte Carlo results only if the superelastic collisions are included in our calculations. Spatially-resolved electron transport properties are calculated using a Monte Carlo simulation technique in order to understand these phenomena.

MW6 39 Dependence of ion drift velocity and diffusion coefficient in parent gas on its temperature* SERGEY MAIOROV, *Joint Institute for High Temperatures of RAS, Moscow* RUSUDAN GOLYATINA, *A.M. Prokhorov General Physics Institute of RAS, Moscow* The results of Monte Carlo calculations of the ion drift characteristics are presented: ions of noble gases and Ti, Fe, Co, Cs, Rb, W and mercury ions in case of constant and uniform electric field are considered. The dependences of the ion mobility on the field strength and gas temperature are analyzed. The parameters of the drift velocity approximation by the Frost formula for gas temperatures of 4.2, 77, 300, 1000, and 2000 K are presented. A universal drift velocity approximation depending on the reduced electric field strength and gas temperature is obtained. In the case of strong electric fields or low gas temperatures, the deviation of the ion distribution function from the Maxwellian one (including the shifted Maxwellian one) can be very significant. The average energies of chaotic motion of ions along and across the electric field can also differ significantly. It is analyzed the kinetic characteristics of ion drift in own gas: ion diffusion coefficient along the field and across the field; thermal spread of velocities (temperature) along the field and across the field. The unexpected and nontrivial fact takes place: collision with backscattering represent only 10-50% of the total number of collisions. This calculation can be used when analyzing experiments with dusty plasma under cryogenic discharge, ultracold plasma.

*The work was supported by the Russian Science Foundation (grant RNF 14-19-01492).

MW6 40 PLASMA SCIENCE

MW6 41 On the role of helium molecules in atmospheric pressure discharges EMILE CARBONE, CHRISTIAN SCHREGEL, DIRK LUGGENHÖLSCHER, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum, 44780 Germany* Despite their intrinsic simplicity, helium plasma kinetics are still not fully understood and quantitatively described. This is particularly the case at high pressures when various molecular helium species (i.e. ions, excimer(s) and Rydberg states) are formed. In this contribution, the absolute density of helium Rydberg molecules is measured for the first time by a combination of laser photoionization and Thomson scattering experiments. The experiments are performed on a parallel plate, nanosecond pulsed, DC discharge at 700 mbar. The results are combined with electron and helium metastable densities measurements and compared with a kinetic model of the discharge. The source of He_2 molecules in the discharge and afterglow phases are identified and discussed. The present experimental data and kinetic model solve several inconsistencies between reaction paths proposed in the literature.

MW6 42 IST-LISBON database with LXCat: Electron scattering cross sections for oxygen and carbon dioxide* M GROFULOVIĆ, V GUERRA, P COCHE, LL ALVES, *IST/IPFN, University of Lisbon, Lisbon* This work proposes sets of electron scattering cross sections compiled for kinetic energies up to 1 keV, as part of the IST-LISBON database with LXCat, for both molecular and atomic oxygen and for carbon dioxide. The complete and consistent sets of cross sections for O_2, O and CO_2 are validated using the two-term Boltzmann solver embedded in LoKI (LisbOn KInetics) numerical code to calculate swarm parameters, yielding fairly good agreement with the available experimental data. It is evidenced that the inclusion of rotational transitions in O_2 and superelastic collisions with $CO_2(010)$ molecules is essential to reproduce the experimental values of the swarm parameters for $E/N<1$ Td. Further improvement can be achieved by deconvolution of the current vibrational excitation cross sections and/or the inclusion of additional vibrational excitation channels, which would also contribute to improve our knowledge of O_2 and CO_2 plasmas.

*This work was partially supported by the Portuguese FCT, under Projects UID/FIS/50010/2013, PTDC/FIS-PLA/1420/2014 and grant PD/BD/105884/2014 (PD-F APPLAuSE).

MW6 43 The electron heating mode transition by the change of driving frequency in atmospheric pressure dielectric barrier discharges JUNG YEOL LEE, *Department of Electrical Engineering, Pusan National University, Busan* JOHN VERBONCOEUR, *Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI* HAE JUNE LEE, *Department of Electrical Engineering, Pusan National University, Busan* Over the past twenty years, micro plasma technology including dielectric barrier discharges (DBDs) brought great enhancement of stable and high density plasma sources in atmospheric pressure environment. However, the experimental diagnostics are difficult to use in atmospheric pressure micro plasmas, and thus the particle-in-cell (PIC) simulation is a good tool to investigate the nonlinear and kinetic effects of the plasma dynamics. In this study, PIC simulation results show that time-dependent parameters compare well with theoretical estimates like energy diffusion theory in the RF frequency ranges up to 500 MHz in atmospheric pressure plasmas for a set of controllable input parameters. Here, alpha-gamma heating mode transition is observed when the driving frequency matches the maximum of energy relaxation frequency by electron impact excitation. The inflection point in a semi-log scaled electron energy probability function (EEPF) is also explained by energy diffusion theory, which corresponds to a transition point of heating mode. Moreover, it was found that extra results in low gas pressure have the same solution at lower input frequency. For this reason, temporal differential term generates non-stationary EEPF in a specific energy range in Boltzmann kinetics.

MW6 44 Azimuthal ExB drift of electrons induced by the radial electric field flowing through a longitudinal magnetic channel with non-magnetized ions HIROSHI AKATSUKA, JUN TAKEDA, ATSUSHI NEZU, *Tokyo Institute of Technology* To examine of the effect of the radial electric field on the azimuthal electron motion under $E \times B$ field for plasmas with magnetized electrons and non-magnetized ions, an experimental study is conducted by a stationary plasma flow. The argon plasma flow is generated by a DC arc generator under atmospheric pressure, followed by a cw expansion into a rarefied gas-wind tunnel with a uniform magnetic field ~ 0.16 T. Inside one of the magnets, we set a ring electrode to apply the radial electric field. We applied an up-down probe for the analysis of the electron motion, where one of the tips is also used as a Langmuir probe to measure electron temperature, density and the space potential. We found that the order of the radial electric field is about several hundred V/m, which should be caused by the difference in the magnetization between electrons and ions. Electron saturation current indicates the existence of the $E \times B$ rotation of electrons, whose order is about $2000 - 4000$ m/s. The order of the observed electron drift velocity is consistent with the theoretical value calculated from the applied magnetic field and the measured electric field deduced from the space potential.

MW6 45 Statistical Physics of Electron Temperature of Low-Pressure Discharge Nitrogen Plasma with Non-Maxwellian EEDF HIROSHI AKATSUKA, *Tokyo Insitute of Technology* YOSHINORI TANAKA, *Mitsubishi Electric Corp.* We reconsider electron temperature of non-equilibrium plasmas on the basis of thermodynamics and statistical physics. Following our previous study on the oxygen plasma in GEC 2015, we discuss the common issue for the nitrogen plasma. First, we solve the Boltzmann equation to obtain the electron energy distribution function (EEDF) $F(\epsilon)$ of the nitrogen plasma as a function of the reduced electric field E/N. We also simultaneously solve the chemical kinetic equations of some essential excite species of nitrogen molecules and atoms, including vibrational distribution function (VDF). Next, we calculate the electron mean energy as $U = \langle\epsilon\rangle = \int_0^\infty \epsilon F(\epsilon) d\epsilon$ and entropy $S = -k \int_0^\infty F(\epsilon) ln[F(\epsilon)] d\epsilon$ for each value of E/N. Then, we can obtain the electron temperature as $T_e^{stat} = [\partial S/\partial U]^{-1}$. After that, we discuss the difference between T_e^{stat} and the kinetic temperature

$T_e^{kin} \equiv (2/3)\langle\epsilon\rangle$, as well as the temperature given as a slope of the calculated EEDF for each value of E/N. We found T_e^{stat} is close to the slope at $\epsilon \sim 4$ eV in the EEPF.

MW6 46 Inter-comparison of calculation techniques of the electron Boltzmann equation for the analysis of swarm parameters in CO_2* M GROFULOVIĆ, N PINHÃO, LL ALVES, V GUERRA, *IST/IPFN, University of Lisbon, Lisbon* D LOFFHAGEN, *Leibniz Institute for Plasma Science and Technology, Germany* I KOROLOV, M VASS, Z DONKÓ, *Institute for Solid State Physics and Optics, Budapest* The plasma-based CO_2 conversion is a promising route for achieving the reduction of fossil fuel consumption and of CO_2 emission. An accurate description of the electron kinetics by solving the electron Boltzmann equation (EBE) is necessary for this application. This work is dedicated to the inter-comparison between various calculation techniques of the EBE (two-term, multi-term and space gradients of the electron density) and the Monte-Carlo reference technique for the analysis of swarm parameters and their comparison with previously available and present experimental data. We adopt the complete set of electron–impact cross sections for CO_2, to be published on the IST-LISBON database with LXCat. Results show that despite the fact that the IST-LISBON cross sections were derived to fit measured swarm parameters when used in a two-term expansion Boltzmann code, good agreement with the other solution and simulation techniques is generally obtained for the electron swarm parameters under consideration.

*Work partially supported by grant OTKA-K-105476 and by Portuguese FCT, under project UID/FIS/50010/2013 and grant PD/BD/105884/2014 (PD-F APPLAuSE).

MW6 47 Effects Of Electrons and Heavy Particles On Halpha Emission In Pure H_2O DC Discharge At High E/N (E-Electric Field, N-Gas Density)* ZORAN PETROVIC, VLADIMIR STOJANOVIC, NIKOLA SKORO, JELENA SIVOS, DRAGANA MARIC, GORDANA MALOVIC, *Inst of Physics, University of Belgrade, P.O. Box 68 11080 Belgrade, Serbia* In this work we present results of Monte Carlo simulations for spatially resolved emission due to the transport of electrons and heavy particles (fast H, H^+, OH^+, H_2O^+,H_3O^+) in pure 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 spatially resolved Halpha emission in H_2O. Data for anisotropic scattering of electrons, ions and fast neutrals are used to obtain contribution to Halpha spatially resolved emission. Agreement with experimental data for drift velocities for all charged particles 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.

*Acknowledgment to Ministry of Education, Science and Technology of Republic Serbia, Projects No. 171037 and 410011.

MW6 48 Numerical Investigation of Propagation and Decay of Fast Ionization Waves Generated by Nanosecond Pulsed Discharge YIFEI ZHU, SVETLANA STARIKOVSKAYA, *LPP, CNRS, Ecole Polytechnique-UPMC-UPSud-UPSay* NATALIE BABAEVA, *Institute for High Temperatures, Russian Academy of Sciences* MARK KUSHNER, *Electrical Engineering and Computer Science Dept., University of Michigan* ELECTRICAL ENGINEERING AND COMPUTER SCIENCE DEPT COLLABORATION, INSTITUTE FOR HIGH TEMPERATURES, RUSSIAN ACADEMY OF SCIENCES COLLABORATION, COLD PLASMA TEAM TEAM Fast ionization waves (FIW) are an effective tool for studying plasma kinetics in nanosecond pulsed discharges. A numerical investigation of FIWs in air having high energy deposition was conducted in capillary tubes having different diameters using a two dimensional model. Continuity equations for charged and neutral species, the electron energy equation and Poisson's equation were implicitly integrated together with a propagator model for photoionization which includes both ionizing and non-ionizing absorption. The species and reactions included in the study were selected on the basis of a sensitivity analysis. The main goals of this work are to quantify how system parameters (e.g., pressure, voltage and specific energy deposition) affect the properties of the plasma in the early afterglow (tens to hundreds of nanoseconds) following the FIW.

MW6 49 Three-body recombination and dynamics of electrons and excited states in the low-pressure argon afterglow* TSANKO VASKOV TSANKOV, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44780 Bochum, Germany* RAINER JOHNSEN, *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA 15260, USA* UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44780 Bochum, Germany* The afterglow phase occurs naturally during the power-off period in pulsed low-pressure plasmas and in atmospheric pressure ns discharges. During that period the electron energy rapidly declines and the charged particles are lost due to diffusion and recombination. In low-pressure discharges the dominant process is three-body recombination (TBR) of Ar^+ ions with electrons. It leads to complex dynamics of the excited states, dominated by collisional-radiative cascades that eventually repopulate the metastable states. In this contribution the afterglow dynamics of an argon discharge is analyzed in detail to elucidate the roles played by the various processes. An analytical model for the fast drop of the electron energy by evaporative cooling and electron-ion collisions is combined with a time-dependent collisional radiative model for the atomic excited states that numerically solves the electron energy and density balance equations. By including further gas heating and cooling, the model leads to excellent agreement with experiments utilizing different diagnostic techniques, and hence gives insight into the interplay of the various processes in the afterglow [1].

*Work Supported by the DFG (Grant No. TS 307/1-1).

[1]Ts. V. Tsankov, R. Johnsen, and U. Czarnetzki, PSST **24**, 065001 (2015).

MW6 50 The effect of realistic surface coefficients on the electron dynamics and process control in simulations of capacitive RF plasmas MANASWI DAKSHA, BIRK BERGER, JULIAN SCHULZE, *Department of Physics, West Virginia University, Institute for Electrical Engineering, Ruhr-University Bochum* ARANKA DERZSI, IHOR KOROLOV, ZOLTAN DONKO, *Hungarian Academy of Sciences* SEBASTIAN WILCZEK, THOMAS MUSSENBROCK, *Institute for Electrical Engineering, Ruhr-University Bochum* In most PIC simulations of capacitively coupled plasmas (CCPs), only an ion induced constant secondary electron emission coefficient, γ, is used, which is usually guessed to be 0.1. Similarly, a constant electron reflection coefficient, ρ, is typically used and assumed to be 0 - 0.2. Here, we utilize an ion and atom induced energy-dependent γ for "dirty" and "clean" surfaces in a single frequency 13.56 MHz CCP. Its effects on electron heating mode transitions are analyzed as a function of pressure. By utilizing the same energy-dependent γ, its effects on the separate control of the ion flux and mean ion energy are studied for a dual frequency (df)

CCP with frequencies of 2 and 27 MHz. The results are compared to multiple simulations with constant γ and significant differences are found. Finally, ρ is varied in a single frequency CCP and its effects on plasma parameters such as the sheath width and electron density are studied. Strong effects of using different reflection probabilities at both electrodes on the discharge symmetry are found. A df CCP is modeled to understand the coupling between the electrical asymmetry effect (EAE) and a discharge asymmetry induced by different electron reflection coefficients for the two electrodes.

MW6 51 Second harmonic wave generation from a nonlinear combination of volume wave and overdense plasma in negative permeability space AKINORI IWAI, YOSHIHIRO NAKAMURA, *Kyoto University* OSAMU SAKAI, *The University of Shiga Prefecture* We clarify the relation between second harmonic wave (SH wave) and plasma generation in various experimental conditions by detecting properties of propagating electromagnetic waves (EM waves). Plasma has a nonlinear reaction against EM wave, generating harmonic waves which depends on electron density n_e. In the case with increased n_e, EM wave comes to be prevented from going into plasma with negative permittivity ε_p. Double-split-ring resonators (DSRRs), one of metamaterials, make permeability μ_D negative. We have shown that EM wave being volume wave can propagate into the combination of overdense plasma and DSRRs because of real negative value refractive index N. In our previous paper [1], we have confirmed enhanced SH wave (4.9 GHz) generation in the composite with 2.45-GHz input. In this report, we show the dependence of the SH wave emission with plasma generation on plasma parameters and gas conditions of plasma. Furthermore, we show the phase change with N variation of the composite space in the case with various input power as the proof of the negative index state.

[1]A. Iwai, Y. Nakamura, and O. Sakai, Phys. Rev. E **92**, 033105 (2015).

MW6 52 Thermoelectric instability of radio-frequency discharges MILES TURNER, *Dublin City University* Spatio-temporal instabilities ("striations") are a ubiquitous feature of direct current discharges, understood to be closely linked to the drift of electrons towards the anode. Similar phenomena are observed in high-frequency discharges, but cannot be understood in the same way, because the drift is absent. Explanations in terms of nonlinear ionization mechanisms, such as multi-step ionization, have been suggested but appear to conflict with some observations. In this work we suggest that a usually neglected transport process may be partly or wholly responsible for these instabilities. This process is known as the thermoelectric effect, which is commonly included in the energy transport equation for semiconductor charge carriers, but not usually in moment models of low-temperature plasmas. An investigation of the the moment equations shows that such an instability is possible, and can be observed in simulations.

MW6 53 Analysis of heavy particle processes in low current dc discharge in water vapor* JELENA SIVOS, DRAGANA MARIC, NIKOLA SKORO, GORDANA MALOVIC, ZORAN LJ PETROVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade* Results presented in our recent paper [1] show that heavy particles – positive ions and fast neutrals (created in charge transfer processes) – can have significant contribution to the processes of excitation at moderate and high reduced electric fields (E/N). In the case of water vapor, hydrogen ions and fast atoms are the most probable candidates, as the lightest products in water vapor discharges. In order to identify dominant heavy species in water vapor discharge, we analyzed discharge parameters in low current Townsend regime. Based on the model developed by Phelps and coworkers in 1993. [2] we were able to estimate transit time of ions from experimentally determined frequency of damped oscillations and parameters of electrical circuit. Furthermore, we compared calculated transit times with transit times of hydrogen ions (H^+, H_2^+, H_3^+) [3]. Initial analysis indicates that H_2^+ is dominant ion in the range of moderate E/N (~2 kTd). Calculations were done for the discharge initiated at electrode gap of 1.1 cm and pressure (p) x gap (d) of 0.6 Torrcm, which corresponds to the conditions of the minimum of Paschen curve. In the next step we will extend the analysis to wider range operating conditions.

*This work is supported by the Serbian MESTD under project numbers ON 171037 and III 41011.

[1]J. Sivoš, *et al*, J. Phys. D: Appl. Phys. **48**, 424011 (2015).
[2]Z. Lj Petrović *et al.*, Phys. Rev. E **47**, 2825 (1993).
[3]A. V. Phelps, J. Phys. Chem. Ref. Data **19**, 653 (1990).

MW6 54 Instabilities in Hall E × B discharges with complex magnetic field configurations A. SMOLYAKOV, O. KOSHKAROV, W FRIAS, I. ROMADANOV, O. CHAPURIN, *University of Saskatchewan* M. UMANSKY, *Lawrence Livermore National Laboratory, USA* Y. RAITSES, I. KAGANOVICH, *Princeton Plasma Physics Laboratory, USA* Hall plasmas with electron **E** × **B** drift exhibit wide range of unstable modes affecting operation and performance of various devices, e.g. such as magnetrons and Hall thrusters. The plasma density, magnetic field and temperature gradients are important source of various gradient-drift and lower-hybrid instabilities across wide range of spatial and temporal scales. The electron response is critically sensitive to the electron dynamics along the magnetic field which has a characteristic frequency scale $k_{\parallel} v_{Te}$. The motion across magnetic field occurs on a slower time scale due to $E \times B$ drift/magnetic drift and/or electron inertial/collisional drifts. The ratio of the transverse to the parallel times scale affects electron dynamics and change the conditions and nature of the instabilities in a significant manner. The nonlinear fluid 3D model has been developed that takes into account both perpendicular and parallel dynamics. Few illustrative examples are considered for the instabilities in various regimes and results of nonlinear simulations in 3D geometries are presented.

MW6 55 Quantitative Defect Analysis of PAN-based Carbon Fibers Treated by Single and Dual HF RF-CCP ÜMMÜGÜL ERÖZBEK GÜNGÖR, *Dr.* This work states the effects of single (40.68 MHz) and dual (40.68/2.1 MHz) RF-CCPs on defect structure of the PAN-based carbon fibers. The fibers were treated between two identical aluminum electrodes with R~200 mm in a 78.5 L stainless steel cylindrical reactor (R~500 mm, H~400 mm). The gap distance was 4 cm. In SRF mode, P_{HF} = 50-200 W, p = 0.3, 0.5, 0.75 and 1 Torr, t = 30, 60 and 90 min. In DRF mode, P_{LF} = 50-200 W, p = 0.1-0.9 Torr and t = 15, 30, 45 and 60 min at fixed P_{HF} = 50 W. The structural analyses of the treated fibers were done by using high sensitive confocal Raman spectroscopy and the surfaces were excited by 532 nm-100 mW He-Ne (2.33 eV) laser. The average defect size and density of the treated fibers were calculated according to the following formulas; L_D (size) = $(1.8 \times 10^{-9} \lambda_L^4 I_G/I_D)^{1/2}$ and n_D (density) = $(1.8 \times 10^{22}/\lambda_L^4) \times I_D/I_G$ where λ_L is the laser wavelength, I_D is the intensity of D-band (\textasciitilde 1350 cm^{-1}) and I_G is the intensity of G-band (~ 1580 cm^{-1}).

MW6 56 Numerical and analytic results showing the suppression of secondary electron emission from velvet and foam,

and a geometric view factor model to guide the development of a surface to suppress SEE* CHARLES SWANSON, I. D. KAGANOVICH, *Princeton Plasma Physics Laboratory* The technique of suppressing secondary electron emission (SEE) from a surface by texturing it is developing rapidly in recent years. We have specific and general results in support of this technique: We have performed numerical and analytic calculations for determining the effective secondary electron yield (SEY) from velvet, which is an array of long cylinders on the micro-scale, and found velvet to be suitable for suppressing SEY from a normally incident primary distribution. We have performed numerical and analytic calculations also for metallic foams, which are an isotropic lattice of fibers on the micro-scale, and found foams to be suitable for suppressing SEY from an isotropic primary distribution. More generally, we have created a geometric weighted view factor model for determining the SEY suppression of a given surface geometry, which has optimization of SEY as a natural application. The optimal surface for suppressing SEY does not have finite area and has no smallest feature size, making it fractal in nature. This model gives simple criteria for a physical, non-fractal surface to suppress SEY. We found families of optimal surfaces to suppress SEY given a finite surface area.

*The research is supported by Air Force Office of Scientific Research (AFSOR).

MW6 57 Computational study of sheath structure in oxygen containing plasmas at medium pressures RUDOLF HRACH, *Faculty of Mathematics and Physics, Charles University* STANISLAV NOVAK, *Faculty of Science, University J.E. Purkinje* TOMAS IBEHEJ, VERA HRACHOVA, *Faculty of Mathematics and Physics, Charles University* Plasma mixtures containing active species are used in many plasma-assisted material treatment technologies. The analysis of such systems is rather difficult, as both physical and chemical processes affect plasma properties. A combination of experimental and computational approaches is the best suited, especially at higher pressures and/or in chemically active plasmas. The first part of our study of argon-oxygen mixtures was based on experimental results obtained in the positive column of DC glow discharge. The plasma was analysed by the macroscopic kinetic approach which is based on the set of chemical reactions in the discharge. The result of this model is a time evolution of the number densities of each species. In the second part of contribution the detailed analysis of processes taking place during the interaction of oxygen containing plasma with immersed substrates was performed, the results of the first model being the input parameters. The used method was the particle simulation technique applied to multicomponent plasma. The sheath structure and fluxes of charged particles to substrates were analysed in the dependence on plasma pressure, plasma composition and surface geometry.

MW6 58 Optical emission spectroscopy of OH lines in N_2 and Ar plasma during the treatments of cotton fabric* NIKOLA SKORO, NEVENA PUAC, KOSTA SPASIC, GORDANA MALOVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia* MARIJA GORJANC, *Department of Textiles, Faculty of Natural Sciences and Engineering, University of Ljubljana, Askerceva 12, 1000 Ljubljana, Slovenia* ZORAN LJ PETROVIC, *Serbian Academy of Sciences and Arts, Knez Mihailova 35, 11000 Belgrade, Serbia* Low pressure non-equilibrium plasmas are proven to be irreplaceable tool in material processing. Among other fields their applications in treatments of textiles are still diversifying, but the main role of plasma is activation of the surface of treated sample. After, or during, the treatments these surfaces can be covered with different materials or species (such as microcapsules) that enhance properties of the fabric. In order to investigate mechanisms how active species from plasma interact with the cotton surface, we studied both plasma and surface properties. Bleached cotton samples were treated in low-pressure nitrogen and argon plasma in a chamber with parallel-plate electrodes. The effect of the plasma treatment on the cotton samples was investigated with the colorimetric measurements on dyes absorption by a spectrophotometer. Optical emission spectroscopy was performed by using spectrometer with a sensitive CCD camera. We have recorded the evolution of the maximum of the intensity of OH and N_2 second positive band lines. Measurement were done with and without samples in the chamber and comparison between the lines intensity was made. The parameters for optimal plasma treatment conditions were determined.

*Research supported by the MESTD, projects III41011 and ON171037.

MW6 59 An Investigation of the Role of Near-Anode Plasma Conditions on Anode Spot Self-Organization in Atmospheric Pressure DC Glows YAO KOVACH, JOHN FOSTER, *University of Michigan - Ann Arbor* In previous work, plasma self-organization patterns were experimentally observed on both liquid surface and metal anode surface in atmospheric pressure glows. However, the origin of the self-organized pattern formation is still poorly understood and is currently under study. In this work, it was observed that the discharge current is the dominant parameter controlling the onset of the self-organization of the plasma attachment on a liquid anode. On the other hand, it is observed that interelectrode spacing is the key parameter that controls plasma self-organization on metal anodes. Presented here are experiments aimed at understanding how these parameters control conditions at the anode surface which ultimately result in self-organization. Here we determine the effects of space charge at the anode surface and also estimate the anode fall voltage in response to discharge parameter variations. Additionally, electron microscopy is used to assess anode morphological changes resulting from the self-organization plasma attachments.

MW6 60 Tomographic reconstruction for plasma diagnostic CHRISTOPHER WAGNER, MARCUS IBERLER, JOACHIM JACOBY, OLIVER MEUSEL, HOLGER PODLECH, ULRICH RATZINGER, *IAP, Goethe-Univerity* HERMINE REICHAU, *None* A tomographic system originally designed for high intensity ion beam diagnostic to reconstructed 3D light density of photons produced by interactions between ion beam and residual gas has been developed and commissioned. In contrast to the classical approach where the beam is rotated in front of the camera, the camera was rotated around the beam and images were taken at multiple angles. The reconstructed light density of each voxel is proportional to the beam particle density at this point. With a inverse radon transformation these images can be transformed to 2D slices through the observed volume. Additionally, a maximum entropy algorithm was implemented due to the potentially very limited number of angles. This concept can be transferred to the diagnostics of classical optical thin plasma. If combined with a shutter camera a suitable monochromator or spectral filters, it should be possible to reconstruct a time and spectral dependent 3D volume of the plasma.

MW6 61 High-resolution TALIF measurements of atomic oxygen: determination of gas temperature and collisional broadening coefficients* JEAN-PAUL BOOTH, DANIIL MARINOV, OLIVIER GUAITELLA, *LPP, CNRS-Ecole Polytechnique-UPMC* CYRIL DRAG, *LAV, CNRS-ENS Cachan-UPsud, France*

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RICHARD ENGELN, *TU Eindhoven, NL* JUDITH GOLDA, VOLKER SCHULTZ-VON DER GATHERN, *Ruhr Universitat Bochum, DE* Two-photon Absorption Laser-Induced Fluorescence (TALIF) is a well-established technique to measure relative (and with appropriate calibration techniques, absolute) densities of atoms in plasmas and flames. The excitation line profiles can provide additional information, but this is usually overlooked due to the mediocre spectral resolution of commercial pulsed dye laser systems. We have investigated O-atom TALIF excitation line profiles using a house-built narrow line-width pulsed UV laser system, based on pulsed Ti:Sa ring laser seeded by a cw infrared diode laser. The observed Doppler profiles allow unambiguous measurement of gas temperature with high precision in O_2 and CO_2 DC glow discharges. Sub-Doppler measurements, performed by reflecting the laser beam back through excitation zone, allow the pressure-broadened line shapes to be observed, both in a pure O_2 DC discharge (up to 10 Torr pressure) and in an atmospheric pressure RF plasma jet in He/O_2. Pressure broadening coefficients of the $3p^3P_J$ state of O were determined for O_2 and He bath gases, and were found to be an order of magnitude bigger than that predicted from the measured quenching rate.

*Work performed in the LABEX Plas@par project, with financial state aid (ANR-11-IDEX-0004-02 and ANR-13-BS09-0019).

MW6 62 Dual frequency diffuse dielectric barrier discharge in atmospheric-pressure air-like gas mixture for thin film deposition YAOGE LIU, *FOM Institute DIFFER* SERGUEI STAROSTIN, *FUJIFILM Manufacturing Europe B.V.* STEFAN WELZEL, M. C. M. VAN DE SANDEN, HINDRIK DE VRIES, *FOM Institute DIFFER* FOM INSTITUTE-DIFFER TEAM, EINDHOVEN UNIVERSITY OF TECHNOLOGY TEAM, FUJIFILM MANUFACTURING EUROPE B.V. TEAM A dual frequency (DF) diffuse discharge was obtained in an atmospheric-pressure dielectric barrier discharge reactor in air-like gas mixtures. By adding a radio frequency (RF) voltage to a low frequency (LF) voltage, we aim to increase the plasma power density. In this study, the discussion is mainly focused on the discharge characteristics and the thin film deposition. According to the spatio-temporal emission, the discharge shows a glow-like structure with both LF and DF voltages. By fitting the spectral lines of the second positive system of N_2, the gas temperature was estimated which does not obviously increase with the extra RF signal. Moreover, SiO_2-like film was deposited from TEOS using the DF power supply. Thin film properties such as surface morphology, microstructure and stoichiometry were analyzed by AFM, FTIR and XPS, respectively. Because of the higher plasma power density, the DF power supply can be an efficient approach to improve the properties and to increase the throughput of the thin film deposition.

MW6 63 Laser absorption velocimetry using an optical vortex beam* SHINJI YOSHIMURA, *National Institute for Fusion Science* MITSUTOSHI ARAMAKI, *Nihon University* NAOYA OZAWA, *Nagoya University* KENICHIRO TERASAKA, MASAYOSHI TANAKA, *Kyushu University* TOMOHIRO MORISAKI, *National Institute for Fusion Science* A plain-wave-like beam, or a Hermite-Gaussian mode, has been used for conventional laser spectroscopy. Since the Doppler shift in frequency of light absorbed by a moving atom is given by the dot product of the wave vector of the light beam and an atomic velocity, it is essentially a one-dimensional measurement. It has a merit that the interpretation of the result is clear and straightforward; however, it simultaneously poses a limitation that the measurable velocity component is confined to the projection along the wave vector. This limitation may be overcome by using an optical vortex beam, or a Laguerre-Gaussian mode, which has helical phase fronts associated with orbital angular momentum of light. Due to its three-dimensional phase structure, the Doppler shift for an atom moving in the optical vortex beam has three components. Therefore, the laser measurement method that has a sensitivity even for transverse motion across the beam is possible to be achieved. We have performed laser absorption measurements using optical vortex beams as a proof-of-principle experiment, where an additional frequency shift in the absorption spectra of metastable argon neutrals in a plasma has been observed. The details of experimental results will be discussed in the conference.

*This study was partially supported by JSPS KAKENHI Grand Numbers 15K05365 and 25287152.

MW6 64 Characterisation of a dielectric barrier surface twin discharge using defined gas mixtures BJÖRN OFFERHAUS, *Ruhr Univ Bochum (AEPT)* FRIEDERIKE KOGELHEIDE, *Ruhr Univ Bochum (BIMAP)* JAN-WILM LACKMANN, NIKITA BIBINOV, *Ruhr Univ Bochum (AEPT)* RYAN SMITH, VERA BRACHT, *Ruhr Univ Bochum (AEPT, BIMAP)* KATHARINA STAPELMANN, *Ruhr Univ Bochum (BIMAP)* PETER AWAKOWICZ, *Ruhr Univ Bochum (AEPT)* AEPT TEAM, BIMAP TEAM In the last decades extensive study has been performed on dielectric barrier discharges (DBDs) in several fields of applications of non-thermal atmospheric pressure plasmas. Their applicability ranges from health-promoting effects to the human skin to air decontamination combined with a rather good scalability [1,2]. Further insight into their physical and chemical properties is mandatory for a proper configuration of plasma sources for a given application. In our case a dielectric barrier surface twin discharge is ignited in different gas mixtures. The surface discharge electrode is made of an Al2O3 plate working as a dielectric barrier and grid-structured copper traces on each side of the plate. The electrode is connected to a HV-HF plasma generator with external transformer. The plasma parameters are determined via OES using an absolutely calibrated Echelle-spectrometer [3].

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[2]A. M. Vandenbroucke, R. Morent, N. De Geyter *et al.*, J. Hazardous Materials **195**, 30 (2011).
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MW6 65 Characterization of a dielectric barrier discharge in controlled atmosphere* FRIEDERIKE KOGELHEIDE, *Ruhr Univ Bochum (BIMAP)* BJÖRN OFFERHAUS, NIKITA BIBINOV, VERA BRACHT, RYAN SMITH, JAN-WILM LACKMANN, PETER AWAKOWICZ, *Ruhr Univ Bochum (AEPT)* KATHARINA STAPELMANN, *Ruhr Univ Bochum (BIMAP)* BIMAP TEAM, AEPT TEAM Non-thermal atmospheric-pressure plasmas are advantageous for various biomedical applications as they make a contact- and painless therapy possible [1]. Due to the potential medical relevance of such plasma sources further understanding of the chemical and physical impact on biological tissue regarding the efficacy and health-promoting effect is necessary. The knowledge of properties and effects offers the possibility to configure plasmas free of risk for humans. Therefore, tailoring the discharge chemistry in regard to resulting oxidative and nitrosative effects on biological tissue by adjusting different parameters is of growing interest. In order to ensure stable conditions for the characterization of the discharge, the used dielectric barrier discharge was mounted in a vessel. Absolutely calibrated optical emission spectroscopy was carried out to analyze the electron density and the reduced electric field [2]. The rather oxygen-based discharge was tuned towards a more nitrogen-based discharge by adjusting several parameters as reactive nitrogen species are known to promote wound healing [3]. Furthermore, the impact of an ozone-free discharge has to be studied [4].

*This work was funded by the German Research Foundation (DFG) with the packet grant PAK 816 'Plasma Cell Interaction in Dermatology'.

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MW6 66 Two-photon absorption laser induced fluorescence measurement of atomic oxygen density in an air atmospheric pressure plasma jet JIM CONWAY, GURUSHARAN GOGNA, STEPHEN DANIELS, *Dublin City University* Two-photon Absorption Laser Induced Fluorescence (TALIF) is used to measure atomic oxygen number density [O] in an air Atmospheric Pressure Plasma Jet (APPJ). A novel technique based on photolysis of O2 is used to calibrate the TALIF system ensuring the same species (O) is probed during calibration and measurement. As a result, laser intensity can be increased outside the TALIF quadratic laser power region without affecting calibration reliability as any high intensity saturation effects will be identical for calibration and experiment. Higher laser intensity gives stronger TALIF signals helping overcome weak TALIF signals often experienced at atmospheric pressure due to collisional quenching. O2 photo-dissociation and two-photon excitation of the resulting [O] are both achieved within the same laser pulse. The photolysis [O] is spatially non-uniform and time varying. To allow valid comparison with [O] in a plasma, spatial and temporal correction factors are required. Knowledge of the laser pulse intensity I0(t), and wavelength allows correction factors to be found using a rate equation model. The air flow into the jet was fixed and the RF power coupled into the system varied. The resulting [O] was found to increase with RF power.

MW6 67 Heated probe diagnostic inside of the gas aggregation nanocluster source* ANNA KOLPAKOVA, ARTEM SHELEMIN, JAROSLAV KOUSAL, PAVEL KUDRNA, MILAN TICHY, HYNEK BIEDERMAN, *Charles University in Prague, Faculty of Mathematics and Physics, V Holešovickách 2, 180 00 Prague 8* SURFACE AND PLASMA SCIENCE TEAM Gas aggregation cluster sources (GAS) usually operate outside common working conditions of most magnetrons and the size of nanoparticles created in GAS is below that commonly studied in dusty plasmas. Therefore, experimental data obtained inside the GAS are important for better understanding of process of nanoparticles formation. In order to study the conditions inside the gas aggregation chamber, special "diagnostic GAS" has been constructed. It allows simultaneous monitoring (or spatial profiling) by means of optical emission spectroscopy, mass spectrometry and probe diagnostic. Data obtained from Langmuir and heated probes map the plasma parameters in two dimensions - radial and axial. Titanium has been studied as an example of metal for which the reactive gas in the chamber starts nanoparticles production. Three basic situations were investigated: sputtering from clean titanium target in argon, sputtering from partially pre-oxidized target and sputtering with oxygen introduced into the discharge. It was found that during formation of nanoparticles the plasma parameters differ strongly from the situation without nanoparticles. These experimental data will support the efforts of more realistic modeling of the process.

*Czech Science Foundation 15-00863S.

MW6 68 Coherent Rayleigh-Brillouin scattering for in situ detection of nanoparticles and large molecules in gas and plasma* A. GERAKIS, *PPPL* M.N. SHNEIDER, *Princeton University* B.C. STRATTON, *PPPL* B. SANTRA, R. CAR, *Princeton University* Y. RAITSES, *PPPL* Laser-based diagnostics methods, such as Spontaneous and Coherent Rayleigh and Rayleigh-Brillouin scattering (SRBS and CRBS), can be used for in-situ detection and characterization of nanoparticle shape and size as well as their concentration in an inert gas atmosphere [1]. We recently developed and tested this advanced diagnostic at PPPL. It was shown that the signal intensity of the CRBS signal depends on the gas-nanoparticle mixture composition, density and the polarizabilities of the mixture components [2]. The measured results agree well with theoretical predictions of Refs [1,2]. In this work, we report the application of this diagnostic to monitor nucleation and growth of nanoparticles in a carbon arc discharge. In support of these measurements, A time-dependent density functional theory was used to compute the frequency-dependent polarizabilities of various nanostructures in order to predict the corresponding Rayleigh scattering intensities as well as light depolarization [3]. Preliminary results of measurements demonstrate that CRBS is capable to detect nanoparticles in volume.

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

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MW6 69 Actinometry of Atomic Fluorine in a Capacitively Coupled Discharge with a mixture of SF_6 and O_2* SHARATH BABU, PAUL SWIFT, STEPHEN DANIELS, MILES TURNER, *Dublin City University* Actinometry is a well-known technique for determining neutral species densities in reactive plasmas using optical emission spectroscopy. The basic idea is to compare the intensity of two emission lines, the first from a species of known density, and second from a species whose density is to be determined. Clearly, this approach succeeds only if the relationship between the relevant line intensities and the species densities is known. Actinometric measurement of atomic fluorine density is of special interest because alternative techniques, such as laser induced fluorescence, are impractically difficult for most purposes. In this paper we discuss actinometric measurement of fluorine densities in mixtures of SF_6 and O_2. In this system, the atomic neutral radical densities are a complex function of the gas mixture. Comparison of the actinometric data with mass spectrometric measurements shows that under many conditions they are proportional, so that ideal actinometric behaviour is observed. We show that this behaviour is predictable on the basis of a recently calculated excitation cross section for fluorine emission line. Hitherto, actinometry of fluorine has depended on difficult empirical calibration procedures.

*Work supported by the Irish Research Council and Intel Ireland Ltd.

MW6 70 Registration of RF Plasma Radiation in Ultra-Violet Range by Solar-blind Photoreceptor SHI NGUYEN-KUOK,* YURY MALAKHOV,† IVAN KOROTKIKH,‡ *None* A spectrum response of a photoreceptor to the RF plasma radiation is determined

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in the present work by means of a spectrophotometer utilizing a gas-filled photoreceptor. A continuous radiation spectrum was observed in the wavelength interval of 190 – 270 nm. The photoreceptor allows measuring of absolute radiation taking into account the spectral sensitivity of the photoreceptor and the values of quantum output for the given wavelength. A continuous spectrum was observed in all three orders of magnitude of diffraction. Develop and test a technique for measuring the intensity of the plasma radiation in the UV wavelength range measured amount of discharge pulses can be used to determine the spectral sensitivity range of UV radiation receivers.

*Professor.
†Associate professor.
‡Student.

MW6 71 Microwave techniques for electron density measurements in low pressure RF plasmas* VIKTOR ZHELTUKHIN, *Kazan National Research Technological University* ILDAR GAFAROV, *Scientific-Development Company "RENARISORB Ltd."* ALEXANDER SHEMAKHIN, *Kazan Federal University* Results of the experimental studying of RF plasma jet at low pressure in the range of 10 - 300 Pa is presented. The electron density distribution both in inductive and in capacitive coupled RF discharges was measured at 1.76 MHz and 13.56 MHz consequently. We used three independent microwave diagnostic techniques such as free space (the "two-frequency" and "on the cut-off signal") and a resonator. It is found that the electron density in the RF plasma jets is by 1-2 orders of magnitude greater than in the decaying plasma jet, and by 1-2 orders of magnitude less than in the RF plasma torch. Thus the RF plasma jet is similar to the additional discharge between the electrodes or the coil and the vacuum chamber walls. As a consequence, the formation of the positive charge sheath near the specimen placed in plasma stream is observed. It is found that the maximum of ionization degree as well as more uniform electron density distribution across the stream is observed in the range of the gas flow rate $G_g = 0.06 - 0.12$ g/s and the discharge power $P_d = 0.5 - 2.5$ kW.

*The work was funded by RFBR, according to the research projects No. 16-31-60081 mol_a_dk.

MW6 72 Investigation of adaptive signal processing methods for denoised I-V curve of Langmuir probe JUNG YEOL LEE, MOON-KI HAN, HO-JUN LEE, HAE JUNE LEE, *Department of Electrical Engineering, Pusan National University, Busan* It is an important issue to obtain a clear second derivative of Langmuir probe I-V curve which involves the electron energy distribution function. Therefore, noise suppressions against random walk of charges are required in the experimental data. Proper numerical methods including fitting, digital smoothing, digital filtering with window function should be used to remove each types of noise to determine electron energy distribution. The calculation of electron energy distributions demands sequential algorithm of several numerical methods to reduce the noise in I-V curve. In this presentation, a new noise suppression method is suggested to achieve advanced Langmuir probe diagnostics. Combined utilization of nonlinear curve fitting and low pass filter with window function shows more precise results than the utilization of smoothing only. Therefore, results including noise analysis algorithm give new guideline of probe diagnostics.

MW6 73 A self-consistent global model of surface wave discharges with cylindrical or co-axial structures: Ar or O_2 fed with continuous or pulse-modulated power input* EFE KEMANECI, *Institute for Theoretical Electrical Engineering, Ruhr University Bochum* FELIX MITSCHKER, MARCEL RUDOLPH, *Institute for Electrical Engineering and Plasma Technology, Ruhr University Bochum* DANIEL SZEREMLEY, DENIS EREMIN, *Institute for Theoretical Electrical Engineering, Ruhr University Bochum* PETER AWAKOWICZ, *Institute for Electrical Engineering and Plasma Technology, Ruhr University Bochum* RALF PETER BRINKMANN, *Institute for Theoretical Electrical Engineering, Ruhr University Bochum* A series of cylindrical and co-axial surface wave discharges fed with either argon or oxygen is modelled by a zero-dimensional global modelling approach. Compared to a recent study of the cylindrical surface-wave discharges [1], a self-consistent estimation of the edge-to-center ratios are analytically defined and extended to include the co-axial structures. The simulation results are compared with the experimental data of the considered discharges for continuous and pulse-modulated power input and a good agreement is obtained.

*Deutsch Bundesministerium fur Bildung und Forschung via PluTO+.

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MW6 74 Monte Carlo simulation of radio-frequency breakdown in oxygen and air* MARIJA SAVIC, DRAGANA MARIC, MARIJA RADMILOVIC-RADJENOVIC, ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade* Radio frequency discharges have been used extensively in the materials processing industry. Nevertheless, processes taking place during the breakdown are still poorly understood. Part of the reason is in large displacement current which prohibits measurements and leaves all to modelling. We have performed detailed simulations using Monte Carlo code, tested in our group, that allows also verification against RF and DC benchmarks and treatment of temporal spatial non-localities. This work contains simulation results of the breakdown voltage curves, Paschen curves. Background gases are oxygen and synthetic air. Electrons were initialized at the point in the middle of the gap and their distribution is evolved in time under the effect of the applied field through Monte Carlo approach. Results qualitatively agree with the available experimental and simulation results. In order to get better insight of the processes leading to the breakdown, spatial distribution of electron energy and concentration as well as rates of ionization and elastic scattering are discussed.

*This work was supported by MESTD Serbia O171037 and III41011 projects.

MW6 75 Plasma Chemistry Reduction from ILDM TAFIZUR REHMAN, *Department of Applied Physics, Eindhoven university of Technology, Eindhoven, The Netherlands* EFE KEMANECI, *Ruhr university Bochum, Theoretical Electrical Engineering, Bochum, Germany* WOUTER GRAEF, *Plasma Matters B.V.* JAN VAN DIJK, *Department of Applied Physics, Eindhoven university of Technology, Eindhoven, The Netherlands* Numerical simulation of plasma models involving large number of species and reactions is computationally expensive. One of the solutions of this problem is to employ Chemical Reduction Techniques (CRT) used in combustion research. The CRT that we apply here is Intrinsic Low Dimensional Manifold (ILDM). ILDM uses the fact that the reaction system is not evenly sensitive to all the reactions, but some reactions are fast and attain steady state in a short interval of time. Based on this information, the ILDM method finds the lower dimensional space inside a complete state-space. After a short time interval the fast processes have relaxed and the densities evolve on a low dimensional manifold of the solution space. Construction of such a lower dimensional manifold allows the reaction space to be described in terms of fewer parameters and it becomes possible to tabulate the results in terms of those parameters. By generating a look-up table for given values of controlling parameters, the remaining parameters are computed explicitly. In this work we apply the ILDM method to argon containing 78 levels. The results are compared with the full simulation. The method is validated by comparison of the results with a traditional collisional radiative model.

MW6 76 Heating dominated inception of pulsed discharges ASHUTOSH AGNIHOTRI, *CWI Amsterdam* WILLEM HUNDSDORFER, *CWI Amsterdam and Radboud University, Nijmegen* UTE EBERT, *CWI Amsterdam and Eindhoven University of Technology, Eindhoven* We simulate the inception of pulsed discharges with heating as the driving agent that leads to spark formation. To understand the phenomenon, we developed a 2D-cylindrically symmetric model that couples the electric discharge dynamics with the background gas dynamics. To capture the ion dynamics well, we reduced the classical drift-diffusion-reaction model of electric discharges to the timescale of ion motion. Additionally, we include secondary emission of electrons from the cathode. We employed the model to study electrical breakdown in air at STP conditions between planar electrodes under the application of pulsed voltages. Our model captures space-charge effects, thermal shocks and induced pressure waves. We observe a cycle of discharge pulses heating the gas and the thermal expansion helping the discharge. This cycle might either lead to spark formation or to discharge decay.

MW6 77 Discontinuous model with semi analytical sheath interface for radio frequency plasma MASARU MIYASHITA, *Sumitomo Heavy Industries, Ltd.* Sumitomo Heavy Industries, Ltd. provide many products utilizing plasma. In this study, we focus on the Radio Frequency (RF) plasma source by interior antenna. The plasma source is expected to be high density and low metal contamination. However, the sputtering the antenna cover by high energy ion from sheath voltage still have been problematic. We have developed the new model which can calculate sheath voltage wave form in the RF plasma source for realistic calculation time. This model is discontinuous that electronic fluid equation in plasma connect to usual passion equation in antenna cover and chamber with semi analytical sheath interface. We estimate the sputtering distribution based on calculated sheath voltage waveform by this model, sputtering yield and ion energy distribution function (IEDF) model. The estimated sputtering distribution reproduce the tendency of experimental results.

MW6 78 Block matrix based LU decomposition to analyze kinetic damping in active plasma resonance spectroscopy* JAN HENDRIK ROEHL, JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lueneburg, Germany* "Active plasma resonance spectroscopy" (APRS) is a widely used diagnostic method to measure plasma parameter like electron density. Measurements with APRS probes in plasmas of a few Pa typically show a broadening of the spectrum due to kinetic effects. To analyze the broadening a general kinetic model in electrostatic approximation based on functional analytic methods has been presented [1]. One of the main results is, that the system response function $Y(\omega)$ is given in terms of the matrix elements of the resolvent of the dynamic operator evaluated for values on the imaginary axis. To determine the response function of a specific probe the resolvent has to be approximated by a huge matrix which is given by a banded block structure. Due to this structure a block based LU decomposition can be implemented. It leads to a solution of $Y(\omega)$ which is given only by products of matrices of the inner block size. This LU decomposition allows to analyze the influence of kinetic effects on the broadening and saves memory and calculation time.

*Gratitude is expressed to the internal funding of Leuphana University.

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MW6 79 A Global PLASIMO Model for H2O Chemistry SAMANEH TADAYON MOUSAVI, PETER KOELMAN, *PhD candidate, Eindhoven University of Technology* WOUTER GRAEF, DIANA MIHAILOVA, *Plasma Matters B. V.* JAN VAN DIJK, *Assistant Professor, Eindhoven University of Technology* EPG/ APPLIED PHYSICS/ EINDHOVEN UNIVERSITY OF TECHNOLOGY TEAM, PLASMA MATTERS B.V. TEAM s Global warming is one of the critical contemporary problems for mankind. Transformation of CO_2 into fuels, like CH_4, that are transportable with the current infrastructure seems a promising idea to solve this threatening issue. The final aim of this research is to produce CH_4 by using microwave plasma in CO_2-H_2O mixture and follow-up catalytic processes. In this contribution we present a global model for H_2O chemistry that is based on the PLASIMO plasma modeling toolkit. The time variation of the electron energy and the species' densities are calculated based on the source and loss terms in plasma due to chemical reactions. The short simulation times of such models allow an efficient assessment and chemical reduction of the H_2O chemistry, which is required for full spatially resolved simulations.

MW6 80 A Robust Compressible Flow Solver for Studies on Solar Fuel Production in Microwave Plasma SAMANEH TADAYON MOUSAVI, PETER KOELMAN, *PhD Candidate, Eindhoven University of Technology* PIETER WILLEM GROEN, *Dutch Institute for Fundamental Energy Research (DIFFER)* JAN VAN DIJK, *Assistant professor, Eindhoven University of Technology* EPG/ APPLIED PHYSICS/ EINDHOVEN UNIVERSITY OF TECHNOLOGY TEAM, DUTCH INSTITUTE FOR FUNDAMENTAL ENERGY RESEARCH (DIFFER) TEAM n order to simulate the dissociation of CO_2 with H_2O admixture by microwave plasma for the production of solar fuels, we need a multicomponent solver that is able to capture the complex nature of the plasma by combining the chemistry, flow, and electromagnetic field. To achieve this goal, first we developed a robust finite volume compressible flow solver in C++. The solver is implemented in the framework of the PLASIMO software and will be used in complete plasma simulations later on. Due to the compressible nature of the solver, it can be used for simulation of dissociation of CO_2 with H_2O admixture by supersonic expansion in microwave plasmas. A spatially second order version of this solver is able to reveal the vortex flow structure of the plasmas. Capabilities of this solver are presented by benchmarking against well-established analytical and numerical test cases.

MW6 81 Influence of SF_6/O_2 inductively coupled plasma parameters on Si etching rates and profiles VIOLETA GEORGIEVA, STEFAN TINCK, ANNEMIE BOGAERTS, *Department of Chemistry, Research group PLASMANT, University of Antwerp* A hybrid 2D Monte Carlo—fluid model, called hybrid plasma equipment model (HPEM) developed by Kushner and co-workers is employed in the present investigation. The model calculates the electron and heavy particle densities, energies and fluxes by solving self-consistently a set of equations including the Maxwell equations, fluid equations, a Monte Carlo procedure or the Boltzmann equation. An additional module, called plasma chemistry Monte Carlo simulation, is used to calculate plasma species fluxes and energy distributions to the substrate to produce detailed information at the substrate level. An analytical module within this hybrid code is addressed to predict the etch rate based on the calculated fluxes and kinetic energies of the different plasma species arriving at the silicon wafer. A detailed SF_6/O_2 chemistry set is used to simulate the electron – heavy particle collisions and a number of reactions. The influence of operating parameters on plasma characteristics, etch rates and profiles is investigated. It is aimed to understand how the etch process influences the contact hole local critical dimension uniformity.

MW6 82 Verification of high performance two-dimensional particle-in-cell simulations of low-temperature plasmas* HUW LEGGATE, MILES TURNER, *Dublin City University* We discuss a two-dimensional implementation of the particle-in-cell algorithm with Monte Carlo collisions. This implementation is designed for multiprocessor environments in which each processor is assumed to offer vector capabilities and multiple execution threads. An appropriate implementation therefore combines OpenMP to exploit multithreading with MPI to coupled computing nodes. This approach promises to achieve accelerations of a least a factor of several hundred, relative to to a simple serial implementation. However, the complexity involved also offers many opportunities for error, and makes correctness demonstrations especially desirable. In this presentation we discuss the characteristics of this parallel implementation, and we describe a suite of verification tests that collectively create a strong presumption that the code is correct.

*Work supported by the EUROfusion consortium.

MW6 83 Predicting ion flux uniformity at the ion extraction plate in a 3D ICP reactor ABHRA ROY, ANANTH BHOJ, *ESI US R&D, Inc.* In order to achieve better control in processing the wafer surface, the ion fluxes in a remote plasma system are often focused through one or more ion extraction plates between the main plasma chamber and the downstream wafer plane. The ion extraction plates are typically of showerhead pattern with multiple holes. The focus of this particular study is to predict the ion flux uniformity over the ion extraction plate for a full 3D inductively coupled discharge reactor model using Argon chemistry. We will use the commercial modeling tool, CFD-ACE+, which can address such a process involving gas flow, heat transfer, plasma physics, reaction chemistry and electromagnetics in a coupled fashion. The plasma characteristics in the chamber and uniformity of the ion fluxes at ion extraction plate are discussed. Parametric studies varying the geometrical dimensions and process conditions to determine the effect on ion flux uniformity are presented. The showerhead-like ion extraction plate will be modeled as a porous media with a specified porosity. Further, a spatially varying porosity of the ion extraction plate is used to simulate ion recombination in order to reduce the ion flux non-uniformity. The goal is to optimize the system maximizing the ion flux while maintaining the uniformity.

MW6 84 Fast multipole and space adaptive multiresolution methods for the solution of the Poisson equation PETR BILEK, *Department of Physical Electronics, Faculty of Science, Masaryk University, Kotlarska 2, 61137 Brno, Czech Republic* MAX DUARTE, *CD-adapco, 200 Shepherds Bush Road, London W6 7NL, UK* DAVID NEČAS, *CEITEC, Masaryk University, Kotlarska 2, 61137 Brno, Czech Republic* ANNE BOURDON, *LPP, UMR 7648, Ecole Polytechnique, route de Saclay, 91128 Palaiseau Cedex, France* ZDENĚK BONAVENTURA, *Department of Physical Electronics, Faculty of Science, Masaryk University, Kotlarska 2, 61137 Brno, Czech Republic* This work focuses on the conjunction of the fast multipole method (FMM) with the space adaptive multiresolution (MR) technique for grid adaptation. Since both methods, MR and FMM provide a priori error estimates, both achieve $O(N)$ computational complexity, and both operate on the same hierarchical space division, their conjunction represents a natural choice when designing a numerically efficient and robust strategy for time dependent problems. Special attention is given to the use of these methods in the simulation of streamer discharges in air. We have designed a FMM Poisson solver on multiresolution adapted grid in 2D. The accuracy and the computation complexity of the solver has been verified for a set of manufactured solutions. We confirmed that the developed solver attains desired accuracy and this accuracy is controlled only by the number of terms in the multipole expansion in combination with the multiresolution accuracy tolerance. The implementation has a linear computation complexity $O(N)$.

MW6 85 Evaluation of the Aleph PIC Code on Benchmark Simulations* JEREMIAH BOERNER, JOSE PACHECO, ANNE GRILLET, *Sandia National Laboratories, Thermal/Fluid Component Sciences* Aleph is a massively parallel, 3D unstructured mesh, Particle-in-Cell (PIC) code, developed to model low temperature plasma applications. In order to verify and validate performance, Aleph is benchmarked against a series of canonical problems to demonstrate statistical indistinguishability in the results. Here, a series of four problems is studied: Couette flows over a range of Knudsen number, sheath formation in an undriven plasma, the two-stream instability, and a capacitive discharge. These problems respectively exercise collisional processes, particle motion in electrostatic fields, electrostatic field solves coupled to particle motion, and a fully coupled reacting plasma. Favorable comparison with accepted results establishes confidence in Aleph's capability and accuracy as a general purpose PIC code. Finally, Aleph is used to investigate the sensitivity of a triggered vacuum gap switch to the particle injection conditions associated with arc breakdown at the trigger.

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

MW6 86 An Upwarming Effect in Rarefied RF Plasma Stream at Low Pressure* VIKTOR ZHELTUKHIN,[†] *Kazan National Research Tecnological University* ALEXANDER SHEMAKHIN,[‡] *Kazan Federal University* ALBERT KHUBATKHUSIN,[§] *Kazan National Research Tecnological University* A mathematical model of the RF plasma flow at 13.3-133 Pa in transition regime at Knudsen $8 \times 10^{-3} \leqslant Kn \leqslant 7 \times 10^{-2}$ and the nozzle pressure ratio $n = 10$ for the carrier gas is described. The model based on both the statistical approach to the neutral component of the RF plasma and the continuum model for electron and ion components. The results of plasma flow calculations performed both for the free flowing and for the sample overflowing at a prescribed electric field are described. The effect of a warming up of a stream in a mixture zone confirmed by comparison of numerical results with experimental ones is found.

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MW6 87 Afivo, a framework for the 2D/3D simulation of streamers and other discharges JANNIS TEUNISSEN, *KU Leuven, Centre for mathematical Plasma Astrophysics and CWI, Amsterdam* MARGREET NOOL, *CWI, Amsterdam* UTE EBERT, *CWI, Amsterdam and Eindhoven Unviversity of Technology* Over the last couple of years we have been developing Afivo, a framework for the simulation of streamers and other discharges in 2D and 3D. The main features of Afivo are: adaptively refined quadtree/octree grids, a geometric multigrid solver, OpenMP parallelism, VTK and Silo output, and an open source license. We have recently focused on improving Afivo's documentation and we have added new examples, which are demonstrated on our poster.

MW6 88 Particle charge distribution in dusty plasmas* MEENAKSHI MAMUNURU, *Lam Research Corporation* ROMAIN LE PICARD, *University of Minnesota* YUKINORI SAKIYAMA, *Lam Research Corporation* STEVEN GIRSHICK, *University of Minnesota* Distribution of charge carried by a nanosized particle in plasma is calculated using zero dimensional Monte Carlo simulations. In this work, several phenomena are taken into account, which place a limit on the negative charge that a nanoparticle can acquire. Electron depletion is seen in plasmas due to electronegativity or due to electron attachment to nanoparticles, and causes particle charge reduction. Secondary electron emission, photo emission place additional limitations on particle charge. Increased positive ion current to particle at higher pressures causes charge reduction [1]. Further, particle size and material dependent charge limits exist – placing a limit on the amount of charge a particle can hold [2]. The effect of all these factors is studied in the context of nanoparticle charge distributions in conditions typically seen in deposition process plasmas. Charge distributions are obtained for a wide range of conditions. The relative importance of each phenomenon in giving rise to significant fractions of non-negative nanoparticles is demonstrated.

*Lam Research Grant.

[1]M. Gatti and U. Kortshagen, Analytical model of particle charging in plasmas over a wide range of collisionality, Phys. Rev. E **78**, 046402 (2008).
[2]R. Le Picard and S. Girshick, The effect of single-particle charge limits on charge distributions in dusty plasmas, J. Phys. D: Appl. Phys. **49**, 095201 (2016).

MW6 89 PIC-DSMC simulation of a triggered vacuum switch with a copper/beryllium cathode* ANDREW FIERRO, CHRIS MOORE, STAN MOORE, LAURA BIEDERMANN, MATTHEW HOPKINS, *Sandia National Laboratories* Typical vacuum discharge simulations rely on the injection of neutral or ionized metal vapor from the cathode into an electrically stressed anode-cathode gap. Simultaneous electron emission, also from the cathode, allows for electron-impact ionization of the emitted metal vapor allowing for plasma formation and subsequent closing mechanism to begin. This work looks to analyze the effect of photoemission from the cathode and/or photoionization of metal vapor on the switch closing process through kinetic simulation techniques. A 500 micron anode-cathode gap is chosen with a variable voltage applied to the anode and a grounded half copper, half beryllium cathode. Injection of the metal vapor for both cathode materials is modeled as a linearly ramped flux with a temperature of 1500 K and a bulk velocity (13.2 km/s for Cu and 22 km/s for Be) away from the cathode. Electron-impact excitation of the emitted metal vapor allows for subsequent spontaneous emission of photons which can then photoionize the metal vapor or cause photoemission from the cathode.

*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 NNSA under contract DE-AC04-94AL85000.

MW6 90 Parametric investigations of plasma characteristics in a remote inductively coupled plasma system PRASOON SHUKLA, ABHRA ROY, KUNAL JAIN, ANANTH BHOJ, *ESI US R&D, Inc.* Designing a remote plasma system involves source chamber sizing, selection of coils and/or electrodes to power the plasma, designing the downstream tubes, selection of materials used in the source and downstream regions, locations of inlets and outlets and finally optimizing the process parameter space of pressure, gas flow rates and power delivery. Simulations can aid in spatial and temporal plasma characterization in what are often inaccessible locations for experimental probes in the source chamber. In this paper, we report on simulations of a remote inductively coupled Argon plasma system using the modeling platform CFD-ACE+. The coupled multiphysics model description successfully address flow, chemistry, electromagnetics, heat transfer and plasma transport in the remote plasma system. The SimManager tool enables easy setup of parametric simulations to investigate the effect of varying the pressure, power, frequency, flow rates and downstream tube lengths. It can also enable the automatic solution of the varied parameters to optimize a user-defined objective function, which may be the integral ion and radical fluxes at the wafer. The fast run time coupled with the parametric and optimization capabilities can add significant insight and value in design and optimization.

MW6 91 Coulomb Collision for Plasma Simulations: Modelling and Numerical Methods JUERGEN GEISER, *Ruhr University of Bochum, Department of Electrical Engineering and Information Technology* We are motivated to model weakly ionized Plasma applications. The modeling problem is based on an incorporated explicit velocity-dependent small-angle Coulomb collision terms into a Fokker-Planck equation. Such a collision is done with so called test and field particles, which are scattered stochastically based on a Langevin equation. Based on such different model approaches, means the transport part is done with kinetic equations, while the collision part is done via the Langevin equations, we present a splitting of these models. Such a splitting allow us to combine different modeling parts. For the transport part, we can apply particle models and solve them with particle methods, e.g., PIC, while for the collision part, we can apply the explicit Coulomb collision model, e.g., with fast stochastic differential equation solvers. Additional, we also apply multiscale approaches for the different parts of the transport part, e.g., different time-scales of an explicit electric field, and model-order reduction approaches. We present first numerical results for particle simulations with the deterministic-stochastic splitting schemes. Such ideas can be applied to sputtering problems or plasma applications with dominant Coulomb collisions.

MW6 92 Electrical and Optical Structural Analysis of Pure Nitrogen RF-CCP ÜMMÜGÜL ERÖZBEK GÜNGÖR, *Dr.* In this work, 13.56 MHz pure (99.995%) nitrogen discharges were generated in a stainless steel cylindrical reactor (R~500 mm, H~400 mm). Two identical aluminum electrodes with R~200 mm were placed in the reactor at a 4 cm gap distance. A High-Resolution HR2000 fiber optic spectrometer (200-1100 nm) was connected to the system to do parametrical analyses. The RF power was in the range of 50-200 W and the pressure was in the range of 0.2-0.7 Torr. I detected many nitrogen atomic lines of N, N^+ and N^{++} in the UV-Vis-NIR spectral regions. Strong N^{++} atomic lines (336.3, 379.45 nm) are mainly dominated the spectrum. Two atomic lines (677.28, 773.26 nm) of the N are ˜four times weaker than that of N^{++}. The atomic lines of the N^+ are ~10 times weaker than that of N^{++}. Also many molecular nitrogen bands, which are the first positive N_2 (B-A) system (530-970 nm), the second positive N_2 (C-B) system (290-531 nm) and the first negative N_2^+ (B-X) system (410-530 nm) are observed. The excitation temperature (T_{exc}) and the electron density (n_e) of the N^+ and N^{++} atomic ions were calculated for each discharge condition.

MW6 93 Two-dimensional PIC/MCC simulation for magnetized capacitively coupled plasmas* HONGYU WANG, PENG SUN, *School of Physics Science and Technology, Anshan Normal University, Anshan, CN* SHALI YANG, WEI JIANG, *Huazhong University of Science and Technology, School of Physics, Wuhan, Hubei, CN* XIANG XU, *Dalian University of Technology, School of physics and optoelectronic engineering, Dalian, CN* Magnetized capacitively coupled plasma (MCCP) has been used in microelectronic industry. In MCP, external static magnetic field is applied on the discharging plasma to improve the plasma confine and adjust the electron energy spectra. Typical about 100's Gauss magnetic field can work well. In these cases, the magnetic confine increase the plasma density and (often) decrease the electron temperature. In this work, we have studied MCCP with two-dimensional Particle-in-cell/Monte Carlo collision (PIC/MCC) model under different gas pressure and magnetic field. All the simulating cases apply external magnetic field in the r and z direction. Electron cooling and the EwB drifting motions are observed. And the effects of magnetic field on the plasma properties, such as the plasma density, electron temperature and energy distribution functions are discussed.

*National Natural Science Foundation of China (11275007, 11105057, 11305032, 11275039).

MW6 94 On the Significance of Metastable States in Low Pressure Capacitively Coupled Oxygen Discharges JON GUDMUNDSSON, HOLMFRIDUR HANNESDOTTIR, *University of Iceland* We use the one-dimensional object-oriented particle-in-cell Monte Carlo collision code oopd1 to explore the spatio-temporal evolution of the electron heating mechanism in a capacitively coupled oxygen discharge in the pressure range 10 – 200 mTorr. The electron heating is most significant in the sheath vicinity during the sheath expansion phase. We explore how including and excluding detachment by the singlet metastable states $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g^+)$ influences the heating mechanism, the effective electron temperature and electronegativity, in the oxygen discharge. We demonstrate that the detachment processes have a significant influence on the discharge properties, in particular for the higher pressures. At 10 mTorr the time averaged electron heating shows mainly ohmic heating in the plasma bulk (the electronegative core) and at higher pressures there is no ohmic heating in the plasma bulk, that is electron heating in the sheath regions dominates.

MW6 95 Etching of Niobium in an Argon-Chlorine Capacitively Coupled Plasma* SVETLANA RADOVANOV, ANA SAMOLOV, *Applied Materials, Varian Semiconductor* JANARDAN UPADHYAY, JEREMY PESHL, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Old Dominion University* APPLIED MATERIALS, VARIAN SEMICONDUCTOR TEAM, OLD DOMINION UNIVERSITY TEAM Ion assisted etching of the inner surfaces of Nb superconducting radio frequency (SRF) cavities requires control of incident ion energies and fluxes to achieve the desired etch rate and smooth surfaces. In this paper, we combine numerical simulation and experiment to investigate Ar /Cl_2 capacitively coupled plasma (CCP) in cylindrical reactor geometry. Plasma simulations were done in the CRTRS 2D/3D code that self-consistently solves for CCP power deposition and electrostatic potential. The experimental results are used in combination with simulation predictions to understand the dependence of plasma parameters on the operating conditions. Using the model we were able to determine the ion current and flux at the Nb substrate. Our simulations indicate the relative importance of the current voltage phase shift and displacement current at different pressures and powers. For simulation and the experiment we have used a test structure with a pillbox cavity filled with niobium ring-type samples. The etch rate of these samples was measured. The probe measurements were combined with optical emission spectroscopy in pure Ar for validation of the model. The authors acknowledge Dr Shahid Rauf for developing the CRTRS code.

*Support DE-SC0014397.

MW6 96 Effect of weak static magnetic field on electron and ion dynamics in low pressure capacitive discharges SARVESHWAR SHARMA, *Institute for Plasma Research, Gandhinagar, Gujarat* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, USA* PREDHIMAN KAW, SANJAY MISHRA, *Institute for Plasma Research, Gandhinagar, Gujarat* ALEXANDER KHRABROV, *Princeton Plasma Physics Laboratory, USA* DMYTRO SYDORENKO, *University of Alberta, Edmonton, Canada* INSTITUTE FOR PLASMA RESEARCH, GANDHINAGAR, GUJARAT TEAM, PRINCETON PLASMA PHYSICS LABORATORY, USA COLLABORATION, UNIVERSITY OF ALBERTA, EDMUNTON, CANADA COLLABORATION We investigated effect of weak static magnetic field applied parallel to electrodes on capacitive discharge in helium making use of the fully self-consistent EDIPIC code. It is observed that without magnetic field both the sheaths are symmetric, but with increase magnetic field, sheath at the grounded electrode gets thinner and the sheath next to the powered electrode become broader and discharge becomes very asymmetric, similar to experimental observations of Ref. [1]. The study of ion velocity distribution functions at the electrode showed that IVDFs can be controlled by a weak magnetic field of order 20G.

[1]S. J. You *et al.*, Thin Solid Films **519**, 6981 (2011).

MW6 97 Effect of dual frequency rf power in an inductively coupled plasma JU-HO KIM, HO-WON LEE, TAE WOO KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Dual frequency inductively coupled plasma discharge is investigated. Dual RF power is applied independently to each antenna (inner and outer coil), and the electron energy distribution functions (EEDFs) are measured using a RF compensated Langmuir probe. As the ratio of low frequency power (P_{low}) and high frequency power (P_{high}) is changed, the variation of EEDF is observed. When P_{low} is higher than P_{high}, the low energy electrons effectively heated compared to the case when P_{low} is comparable to P_{high}. This difference in the shape of the EEDF can be understood by correlation between the driving frequency and the collision frequency.

MW6 98 Plasma characteristics in inductively and capacitively coupled hybrid source using single RF power KWAN-YONG KIM, *Department of Electrical Engineering Hanyang University* MOO-YOUNG LEE, *Department of Nanoscale Semiconductor Engineering Hanyang University* TAE-WOO KIM, JU-HO KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering Hanyang University* Parallel combined inductively coupled

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plasma (ICP) and capacitively coupled plasma (CCP) using single RF generator was proposed to linear control of the plasma density with RF power. In the case of ICP, linear control of the plasma density is difficult because there is a density jump up due to E to H transition. Although the plasma density of CCP changes linearly with power, the density is lower than that of ICP due to high ion energy loss at the substrate. In our hybrid source, the single RF power generator was connected to electrode and antenna, and the variable capacitor was installed between the antenna and the power generator to control the current flowing through the antenna and the electrode. By adjusting the current ratio between the antenna and the electrode, linear characteristic of plasma density with RF power is achieved.

MW6 99 On the optimal chamber length and electron heating mechanism in low pressure inductive discharges HYUN-JU KANG, KYUNG-HYUN KIM, HO-WON LEE, IL-SEO PARK, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Plasma resistance with the chamber length was measured at different plasma densities in low pressure inductively coupled plasmas. It was found that the plasma resistance has a maximum at specific chamber length, L_{opt}, and the L_{opt} is changed with the plasma density. It is related to the maximum collisionless electron heating, which simultaneously satisfies the conditions of both the bounce resonance and the transit time resonance. Therefore, L_{opt} is an optimal chamber size for the power transfer to the plasma.

MW6 100 Effect of complex permeability of ferrite material to the plasma discharge in a large size ferrite inductively coupled plasma HYUNJUN KIM,* *Hanyang University* For the investigation in effect of the complex permeability to the ferrite inductively coupled plasma (Ferrite ICP), three different types of the ferrite material were adopted. Although the strength of the inductive coupling with the plasma can be improved the higher permeability, the plasma density can be reduced by higher permeability when the antenna resistance is higher enough to offset positive effect of it.

*Department of Electrical Engineering, Hanyang university, Seoul 133-791, Republic of Korea.

MW6 101 Model reduction for streamer coronas UTE EBERT, *CWI Amsterdam and Eindhoven Univ Tech, Netherlands* JANNIS TEUNISSEN, *CWI Amsterdam, Netherlands* ALEJANDRO LUQUE, *Instituto de Astrofisica de Andalucia (IAA), CSIC, Granada, Spain* Pulsed gas discharges in nature and technology can consist of hundreds to ten thousands of streamers. Such streamer coronas up to now are modeled in a phenomenological manner; a model setup to include more microscopic information was provided by Luque and Ebert [1]. To implement the proper microphysics, we here analyze the interior dynamics of propagating streamer heads, we review, unify and extend earlier analytical approximations, and we compare them with fluid simulation results derived with the Afivo computational framework http://www.cwimd.nl/doku.php?id=codes:afivo developed by Teunissen.

[1]Luque and Ebert, New J. Phys. **16**, 013039 (2014).

MW6 102 N2(A) vibrational kinetics in streamer discharges: effect of oxygen on formation of low vibrational levels* MILAN SIMEK, *Institute of Plasma Physics of the CAS, Prague, Czech Republic* PAOLO FRANCESCO AMBRICO, *PLASMI lab @ CNR Nanotec* VACLAV PRUKNER, *Institute of Plasma Physics of the CAS, Prague, Czech Republic* In the present study we report on the N2(A) vibrational kinetics in nitrogen-oxygen mixtures revealed by LIF technique under DBD streamer discharge conditions at low pressures. In pure nitrogen, the observed evolution of the N2(A) LIF signal during the decaying streamer channel period evidences fast initial relaxation of high vibrational levels towards the v = 2 and 3 levels, followed by a delayed increase of terminal v = 0 and 1 levels. In nitrogen-oxygen mixtures however, the efficient quenching of higher N2(A) levels by oxygen significantly inhibits vibrational relaxation towards the lower and terminal levels, causing much lower populations of the v = 0–3 levels. This is already clearly visible in the N2 + 0.8% O2 mixture with all the kinetics limited to the first 10 microseconds. In synthetic air, the kinetics is limited to few microseconds in the post discharge. Furthermore, much more effective quenching of fluorescence makes the measurements extremely challenging. Obtained results show that with the addition of oxygen the evolution of the N2(A) vibrational distribution is effectively terminated during the collisional-radiative cascade inhibiting energy pooling mechanism which is effective in pure nitrogen

*Work supported by GACR (Contract No. GA15-04023S).

MW6 103 Discharge modes of a DC operated atmospheric pressure air plasma jet JUERGEN KOLB, *Leibniz Institute for Plasma Science and Technology* XUEKAI PEI, *Huazhong University of Science and Technology* JANA KREDL, *Leibniz Institute for Plasma Science and Technology* XINPEI LU, *Huazhong University of Science and Technology* By flowing air or nitrogen through a microhollow cathode discharge geometry an afterglow plasma jet can be generated at atmospheric pressure in air. The plasma jet has been successfully used for the inactivation of bacteria and yeast. The responsible reaction chemistry is based on the production of high concentrations of nitric oxide. Production yields depend in particular on gas flow rate and energy dissipated in the plasma. The same parameters also determine different modes of operation for the jet. A true DC operation is achieved for low to moderate gas flow rate of about 1 slm and discharge currents on the order of 10 mA. When increasing the gas flow rate to 10 slm the operation is changing to a self-pulsing mode with characteristics similar to the ones observed for a transient spark. By increasing the current a DC operation can be achieved again also at higher gas flow rates. The parameter regimes for different modes of operation can be described by the reduced electric field E/N.

MW6 104 Characteristics of the Plasma Environment and Discharge Process in a High-Pressure Pulsed Arc Discharge RICKY TANG, MATTHEW HOPKINS, EDWARD BARNAT, *Sandia National Labs* The characteristics and properties of a plasma generated in a pulsed arc discharge are investigated. Arc discharge plasmas are prevalent in the production and treatment of materials. Photodetectors and optical emission spectroscopy (OES) are used to probe the plasmas and characterize their spectral responses. OES allows for species identification and provides information about the state of the plasma, such as the electron temperature. Discharges generated with inert gas such as argon, as well as with nitrogen and air, are studied and compared. In the case of reactive gases, OES also provides information on the possible reactions that took place. Microwave interferometry is used to measure the electron density to provide spatial information on the discharges. In addition, the measurement is synchronized with the discharge pulse to obtain temporal information, for instance, during the pulse initialization phase to investigate the arc discharge process prior to plasma generation, where optical information is absent. Together, this allows for the characterization of the pre-, during, and post-discharge processes.

MW6 105 PLASMA APPLICATIONS

MW6 106 High speed deposition of SiO_2 film by slot-type microwave CVD system* HIROTAKA TOYODA, MASAKI YAMAMOTO, HARUKA SUZUKI, *Nagoya University* High density microwave plasma is attractive because of its ability for high-throughput processing. So far, we have successfully produced large-area surface wave excited plasma (SWP) and have applied it to plasma-enhanced chemical vapor deposition (PE-CVD) of silicon films. However, the SWP requires a dielectric plate for the surface wave propagation, and high density plasma sometimes erodes the dielectric plate to produce oxygen contamination. To avoid such problem, we propose the PE-CVD using the microwave plasma produced inside slots of a waveguide without using the dielectric plate. A 2.45 GHz pulsed microwave (repetition: 20 kHz, duty ratio: 20%, average power: 40 W) is introduced to a rectangular waveguide through an isolator, a tuner, and a vacuum window. A slot of 4 mm in length and 0.2 mm in width is placed at the end of the waveguide, and is connected to a vacuum chamber. Both the waveguide and the chamber are evacuated by a turbomolecular pump. Oxygen and tetraethyl orthosilicate (TEOS) gases are introduced from the waveguide and from the outside of the waveguide, respectively, to deposit SiO_2 film on Si substrates at a pressure of 15 Torr and a slot-substrate distance of 1.1 cm. Deposition rate as high as 80 nm/s is observed at a TEOS flow rate of 0.8 sccm. The result suggests that the present PE-CVD system is promising as a new high-speed film deposition technique.

*Part of this work is supported by JSPS KAKENHI Grant Number 25286079.

MW6 107 Investigation of neutral and ion dynamics in a HiPIMS plasma by tunable laser diode absorption spectroscopy (TDLAS) PATRICK PREISSING, ANTE HECIMOVIC, ACHIM VON KEUDELL, *Ruhr-Universität Bochum* High power impulse magnetron sputtering (HiPIMS) discharges are known for complex plasma interactions, and complex temporal and spatial dynamics. Spatial and temporal dynamic of argon metastable (Ar^m), Ti atom (Ti^0) and Ti ion (Ti^+) density and temperature is studied by an extended tunable diode laser absorption spectroscopy setup (TDLAS) during a HiPIMS pulse. The TDLAS setup used a beam expander in combination with a 6 photo diode array to simultaneously measure spatial (resolution 5 mm) and time resolved absorption profiles of an Ar^m, Ti^0 and Ti^+ transition. This in combination with moving the magnetron in axial direction gives a complete 2D map of the density evolution. Temporal resolution of 400 ns was achieved by recording the photo diode signal on the National Instruments card. Final results allowed to investigate temporal evolution of the observed species in the volume between the target and the substrate.

MW6 108 Moved to FT4.002

MW6 109 Nanoparticle formation and thin film deposition in aniline containing plasmas CEDRIC PATTYN, *GREMI UMR 7344 CNRS&Universite d'Orleans, France* ANA DIAS, *Instituto Superior Técnico, Technical University of Lisbon, Portugal* SHAHZAD HUSSAIN, *GREMI UMR 7344 CNRS&Universite d'Orleans, France* THOMAS STRUNSKUS, *University of Kiel, Kiel, Germany* ILIJA STEFANOVIC, CHANTAL BOULMER-LEBORGNE, THOMAS LECAS, EVA KOVACEVIC, JOHANNES BERNDT, *GREMI UMR 7344 CNRS&Universite d'Orleans, France* This contribution deals with plasma based polymerization processes in mixtures of argon and aniline. The investigations are performed in a capacitively coupled RF discharge (in pulsed and continuous mode) and concern both the observed formation of nanoparticles in the plasma volume and the deposition of films. The latter process was used for the deposition of ultra-thin layers on different kind of nanocarbon materials (nanotubes and free standing graphene). The analysis of the plasma and the plasma chemistry (by means of mass spectroscopy and in-situ FTIR spectroscopy) is accompanied by several ex-situ diagnostics of the obtained materials which include NEXAFS and XPS measurements as well as Raman spectroscopy and electron microscopy. The decisive point of the investigations concern the preservation of the original monomer structure during the plasma polymerization processes and the stability of the thin films on the different substrates.

MW6 110 Underwater plasma discharge and its water treatment applications SUKHWAL MA, JIN YOUNG HUH, KANGIL KIM, YONG CHEOL HONG, *National Fusion Research Institute* NATIONAL FUSION RESEARCH INSTITUTE TEAM, CHONBUK NATIONAL UNIVERSITY TEAM, KWANGWOON UNIVERSITY TEAM, NPAC TEAM In recent, the quality of water has been exacerbated by the influx of wastewater and water pollutants. There have been frequent occurrences of water blooms due to the eutrophication of river. Therefore, the needs for water treatment are increased through effective and environment-friendly method. In this work, we propose the plasma system to overcome the problems mentioned above using underwater discharge plasma. The underwater discharges are generated by capillary electrode, and have the advantages of low cost, high efficiency and eco-friendly processing. The proposed technologies can be suitable for eliminating cyanobacteria, decreasing the concentration of oil dissolved in water, and purifying wastewater. Cyanobacteria is killed directly by the underwater discharge and water-dissolved oil and heavy-metal wastewater are purified by coagulation effect, which may result from the chemical reactions of underwater plasma. Consequently, these technologies using underwater discharge can be alternative methods to replace the existing technologies.

MW6 111 Design of experiment analysis of CO_2 dielectric barrier discharge conditions on CO production* MARKUS BECKER, *INP Greifswald, 17489 Greifswald, Germany* SRINATH PONDURI, *Dutch Institute for Fundamental Energy Research, 5612 AJ Eindhoven, The Netherlands* RICHARD ENGELN, *Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands* RICHARD VAN DE SANDEN, *Dutch Institute for Fundamental Energy Research, 5612 AJ Eindhoven, The Netherlands* DETLEF LOFFHAGEN, *INP Greifswald, 17489 Greifswald, Germany* Dielectric barrier discharges (DBD) are frequently used for the generation of CO from CO_2 which is of particular interest for syngas production. It has been found by means of fluid modelling in [1] that the CO_2 conversion frequency in a CO_2 DBD depends linearly on the specific energy input (SEI) while the energy efficiency of CO production is only weakly dependent on the SEI. Here, the same numerical model as in [1] is applied to study systematically the influence of gas pressure, applied voltage amplitude and frequency on the CO_2 conversion frequency and the energy efficiency of CO production based on a 2-level 3-factor full factorial experimental design. It is found that the operating conditions of the CO_2 DBD for

CO production can be chosen to either have an optimal throughput or a better energy efficiency.

*This work was partly supported by the German Research Foundation within the Collaborative Research Centre Transregio 24.

[1]S. Ponduri *et al.*, J. Appl. Phys. **119**, 093301 (2016).

MW6 112 Carbon dioxide reduction in low-pressure ICP STANISLAV DUDIN, ALEXANDER DAKHOV, *V.N. Karazin Kharkiv National University* This work experimentally investigates the efficiency of carbon dioxide dissociation in inductively coupled plasma (ICP) at low gas pressure. The plasma source operates at 13.56 MHz in the RF power range of 100-500 W. Pure CO_2 is fed into the plasma while the output gas composition is measured by a mass spectrometer. The pressure range inside the source was changed in the range of 1-200 mTorr. Excitation processes in the plasma are studied by means of optical emission spectroscopy, and the plasma density along with the electron temperature are monitored using a Langmuir probe. Experimental results have shown that the conversion efficiency of CO_2 to CO and O_2 increases with the RF and reaches the values more than 50%. A theoretical treatment of the dissociation pathway is also given allowing estimation of the mean dissociation length of the carbon dioxide molecule in plasma. The plasma parameters necessary for efficient CO_2 reduction are discussed.

MW6 113 Valorization of biogas into liquid hydrocarbons in plasma-catalyst reactor* MEHRDAD NIKRAVECH, ABDELKADER RAHMANI, SANA LABIDI, NOIRIC SAINTINI, *LSPM-CNRS, Université Sorbonne Paris Cité, P13* Biogas represents an important source of renewable energy issued from biological degradation of biomass. It is planned to produce in Europe the amount of biogas equivalent to 6400 kWh electricity and 4500 kteo (kilo tons equivalent oil) in 2020. Currently the biogas is used in cogeneration engines to produce heat and electricity directly in farms or it is injected in gas networks after purification and odorisation. The aim of this work is to propose a third option that consists of valorization of biogas by transformation into liquid hydrocarbons like acetone, methanol, ethanol, acetic acid etc. These chemicals, among the most important feed materials for chemical industries, retain CO_2 molecules participating to reduce the greenhouse gas emissions and have high storage energy capacity. We developed a low temperature atmospheric plasma-catalyst reactor (surface dielectric barrier discharge) to transform biogas into chemicals. The conversion rates of CH_4 and CO_2 are respectively about 50% and 30% depending on operational conditions. The energetic cost is 25 eV/molecule. The yields of liquid hydrocarbon reaches currently 10% wt. More the 11 liquid chemicals are observed in the liquid fraction.

*Acknowledgements are due to SPC Programme Energie de demain.

MW6 114 Understanding the vibrational distribution in CO_2 microwave plasma for production of carbon neutral fuels, using time resolved in-situ spectroscopy DIRK VAN DEN BEKEROM, TEOFIL MINEA, NICOLA GATTI, FLORAN PEETERS, ERWIN ZOETHOUT, TINY VERREYCKEN, WALDO BONGERS, RICHARD VAN DE SANDEN, GERARD VAN ROOIJ, *FOM Institute DIFFER* A microwave plasma could prove to be a cost effective way of converting CO_2 to CO. The efficiencies of such a reactor have been shown to be very high, up to 90%. It is currently understood that the preferable vibrational excitation by plasma electrons plays a key role in the efficient CO_2 conversion. In the case that Vibrational-Vibrational (VV) relaxation times are much shorter than Vibrational-Translational (VT) relaxation times, molecules are vibrationally excited via intermolecular collisions until the dissociation energy is reached. As the VT-relaxation rate increases with temperature, a low temperature is needed to promote an overpopulation of high vibrational levels. To reduce the temperature, The microwave power was pulsed. Raman-scattering was employed to measure the temperature in the radial center and sides of the plasma, over an axial distance of a few centimeter. The infrared absorption spectrum of the CO_2-plasma is recorded using an in-situ step-scan FTIR spectrometer. The absorption bands of higher vibrational levels are visible lower wavenumbers, down to 2000 cm^{-1}. This enables us to look at the evolution of the densities of the vibrational levels. It was found that the vibrational temperature increased during plasma ON-time.

MW6 115 Development of atmospheric pressure large area plasma jet for sterilisation and investigation of molecule and plasma interaction KRISTINA ZERBE, MARCUS IBERLER, JOACHIM JACOBY, CHRISTOPHER WAGNER, *IAP, Goethe-University* The intention of the project is the development and improvement of an atmospheric plasma jet based on various discharge forms (e.g. DBD, RF, micro-array) for sterilisation of biomedical equipment and investigation of biomolecules under the influence of plasma stress. The major objective is to design a plasma jet with a large area and an extended length. Due to the success on small scale plasma sterilisation the request of large area plasma has increased. Many applications of chemical disinfection in environmental and medical cleaning could thereby be complemented. Subsequently, the interaction between plasma and biomolecules should be investigated to improve plasma strerilisation. Special interest will be on non equilibrium plasma electrons affecting the chemical bindings of organic molecules.

MW6 116 Comparative study of non-thermal atmospheric pressure discharge plasmas for life science applications KAZUNORI KOGA, RYU KATAYAMA, THAPANUT SARINONT, HYUNWOONG SEO, NAHO ITAGAKI, *Kyushu University* PANKAJ ATTRI, *Kwangwoon University* EDBERTHO LEAL-QUIROS, *University of California Merced* AKIYO TANAKA, MASAHARU SHIRATANI, *Kyushu University* We are comparing several non-thermal atmospheric pressure discharge plasmas for life science applications. Here we measured discharge period dependence of pH value and 750 nm absorbance of KI-starch solution of deionized water after plasma irradiation with two discharge devices; a dielectric barrier discharge (DBD) jet device and a scalable DBD device [1]. The pH and the absorbance of KI-starch solution are useful indicator of their oxidizability [2, 3]. We have obtained a map of the absorbance and proton concentration $[H^+]$ which is deduced from pH value. For the scalable DBD, the range of the absorbance is between 0.7 and 1.3 and that of $[H^+]$ is between 10^{-7} and 10^{-5} mol/L. For the DBD jet, the range of the absorbance and $[H^+]$ are 2.0-3.2 and 10^{-4}-10^{-3} mol/L, respectively. Measured data for both devices shows same tendency in the map, while the range of values for the scalable DBD is smaller than that for the DBD jet. The results indicate the oxidazability for the scalable DBD is much weaker than that for the DBD jet.

[1]S. Kitazaki *et al.*, Curr. Appl. Phys. **14**, S149 (2014).
[2]T. Sarinont *et al.*, JPS Conf. Proc. **1**, 015078 (2014).
[3]T. Kawasaki *et al.*, J. Appl. Phys. **119**, 173301 (2016).

MW6 117 Trial of Growth Control of Farm-raised Fish by Plasma-generated Reactive Species* HIDEKI MOTOMURA, YOSHIKI KUBOTA, RYO FUKUSHIMA, YOSHIHISA IKEDA, MASAFUMI JINNO, *Ehime University* As one of the biological applications of plasmas, growth control of agricultural products attracts attentions. There are many papers on growth enhancement of crops by plasma treatment. However, there are few published papers concerning growth enhancement of fishery products excepting reports of goldfish growth enhancement in 1980s. In this study, growth characteristics of edible fish (tilapia) under the plasma treatment has been investigated. An arc discharge reactor was employed and plasma treated air was introduced to two aquariums with a flow rate of 2.5 L/min. Measured concentrations of main reactive species were 43 ppm for NO, 23 ppm for NO_2 and 7.5 ppm for O_3. Each aquarium had 60 L capacity and contained 15 tilapia fish. The plasma treated air was supplied to an aquarium once a day and to the other aquarium twice a day with total duration of 10 min. Compared to no plasma treatment case, the growth rate decreased by 18% by once a day plasma treatment, whereas almost same growth rate was observed by twice a day plasma treatment. A possible reason of growth suppression is excess concentrations of nitrite and nitrate in water. The relationship between their concentrations and growth characteristics under several treatment conditions will be shown at the conference.

*Tirapia fish was supplied from SEFREC of Ehime University.

MW6 118 Investigation of relationship between plasma gas temperature and reactive species HIDEYUKI DOYAMA, HIROAKI KAWANO, *FIRST, Tokyo Institute of Technology* TOSHIHIRO TAKAMATSU, *Graduate School of Medicine, Kobe University* YURIKO MATSUMURA, *Tokyo Healthcare University Postgraduate School* HIDEKAZU MIYAHARA, *FIRST, Tokyo Institute of Technology* ATSUO IWASAWA, *Tokyo Healthcare University Postgraduate School* TAKESHI AZUMA, *Graduate School of Medicine, Kobe University* AKITOSHI OKINO, *FIRST, Tokyo Institute of Technology* In recent years, atmospheric non-thermal plasmas have attracted attention as a new sterilization device. In conventional plasma source, since the plasma gas temperature depends on the discharge power, influence of the plasma gas temperature on bactericidal ability by constant power has not been investigated. Therefore, we developed a new plasma source that can control the plasma gas temperature independently of the power, and it was shown that the bactericidal ability is increased with the plasma gas temperature. However, this factor has not been revealed. In this study, we investigated relationship between the bactericidal ability and the concentration of reactive species at each plasma gas temperature. Because reactive species generated by plasma are thought to affect sterilization. So, to investigate lifetime of the sterilizing factor bactericidal ability of Plasma Treated Water made by each gas temperature plasma was investigated. In both experiments, the correlation ($R^2 = 0.999$) was observed between the concentration of singlet oxygen ($^1O_2$) and the bactericidal ability. These results show long-lifetime reactive species generated by $^1O_2$ affects the bactericidal ability.

MW6 119 Impact of electric field from a plasma jet on biological targets CLAIRE DOUAT, THIBAULT DARNY, SYLVAIN ISENI, XAVIER DAMANY, SEBASTIEN DOZIAS, JEAN-MICHEL POUVESLE, ERIC ROBERT, *GREMI UMR7344CNRS University of Orleans, France* VINODINI VIJAYARANGAN, ANTHONY DELALANDE, CHANTAL PICHON, *CBM, UPR 4301 CNRS Orleans, France* Atmospheric pressure plasma jets have demonstrated their ability in biomedical applications thanks to their low gas temperature and their capacity to produce radicals, ions, electrons, UV radiation and electric fields. However the understanding of the interactions between the plasma and living cells and tissues is still far from being completely understood. Recently, Robert *et al* characterized two components of the electric field from a plasma jet and showed that the latter can propagate deeply in tissues on several mm [1]. In this work, we focus on the study of the electric field induced by the plasma and its influence on the cell membrane. Propidium iodide, dextran sulfate and plasmid DNA are used to measure the permeability of the membrane, while an electro-optic probe is used to measure the longitudinal and the radial components of the electric field. The two components are both spatially and temporally resolved. To investigate the contribution of the electric field on the cell membrane, a dielectric barrier is used between the plasma and the biological target. A comparison with and without the barrier will be presented for both biological and agriculture applications.

[1]E. Robert *et al*, Phys. Plasmas **22**, 122007 (2015).

MW6 120 Anti-tumor Effects of Plasma Activated Media and Correlation with Hydrogen Peroxide Concentration MOUNIR LAROUSSI, SOHEILA MOHADES, NAZIR BAREKZI, VENKAT MARUTHAMUTHU, HAMID RAZAVI, *Old Dominion University* Plasma activated media (PAM) can induce death in cancer cells. In our research, PAM is produced by exposing liquid culture medium to a helium plasma pencil. Reactive oxygen and nitrogen species in the aqueous state are known factors in anti-tumor effects of PAM. The duration of plasma exposure determines the concentrations of reactive species produced in PAM. Stability of the plasma generated reactive species and their lifetime depend on parameters such as the chemical composition of the medium. Here, a complete cell culture medium was employed to make PAM. Later, PAM was used to treat SCaBER cancer cells either as an immediate PAM (right after exposure) or as an aged-PAM (after storage). SCaBER (ATCC®HTB-3™) is an epithelial cell line from a human bladder with the squamous carcinoma disease. A normal epithelial cell line from a kidney tissue of a dog - MDCK (ATCC®CCL-34™) - was used to analyze the selective effect of PAM. Correspondingly, we measured the concentration of hydrogen peroxide- as a stable species with biological impact on cell viability- in both immediate PAM and aged-PAM. In addition, we report on the effect of serum supplemented in PAM on the H_2O_2 concentration measured by Amplex red assay kit. Finally, we evaluate the effects of PAM on growth and morphological changes in MDCK cells using fluorescence microscopy.

MW6 121 Optical Characteristics Investigation of the Cold Argon Plasma Jet for the Medical Applications SHI NGUYEN-KUOK, YURY MALAKHOV, SY MINH BACH, IVAN KOROTKIKH, *None* The medical setup was designed for the treatment of wounds, disinfection of inflammation, for the destruction of damaged cells. The results of experimental determination of the optical characteristics of Argon cold plasma at atmospheric pressure are presented in the paper. The main components of the experimental setup are plasma torch, spectrometer, photo-electron multiplier, oscilloscope, gas consumption $Q_{Ar} = 1 - 20$ l/min. Spectrum of the plasma jet is obtained using the grating spectrometer Spectra with radiometric calibration, operating in the visible range $\lambda = 380 - 760$ nm. The sun-blind photodetector was used for determination of the intensity of radiation in the UV range $\lambda = 190 - 380$ nm. The emission spectrum consists of a continuous radiation and the emissions of atoms and ions ArI and ArII. The analysis of spectral lines was carried out.

MW6 122 DSMC simulations of leading edge flat-plate boundary layer flows at high Mach number DR. SAHADEV PRADHAN, *Dept. of Chemical Engineering, Indian Institute of Science,* *Bangalore-560 012, India* The flow over a 2D leading-edge flat plate is studied at Mach number $Ma = (U_{inf}/\sqrt{k_B T_{inf}/m})$ in the range $<Ma<10$, and at Reynolds number number $Re= (L_T U_{inf} \rho_{inf})/ mu_{inf}$ equal to 10^c using two-dimensional (2D) direct simulation Monte Carlo (DSMC) simulations to understand the flow phenomena of the leading-edge flat plate boundary layer at high Mach number. Here, L_T is the characteristic dimension, U_{inf} and T_{inf} are the free stream velocity and temperature, rho_{inf} is the free stream density, m is the molecular mass, mu_{inf} is the molecular viscosity based on the free stream temperature T_{inf}, and k_B is the Boltzmann constant. The variation of streamwise velocity, temperature, number-density, and mean free path along the wall normal direction away from the plate surface is studied. The qualitative nature of the streamwise velocity at high Mach number is similar to those in the incompressible limit (parabolic profile). However, there are important differences. The amplitudes of the streamwise velocity increase as the Mach number increases and turned into a more flatter profile near the wall. There is significant velocity and temperature slip ((Pradhan and Kumaran, J. Fluid Mech-2011); (Kumaran and Pradhan, J. Fluid Mech-2014)) at the surface of the plate, and the slip increases as the Mach number is increased. It is interesting to note that for the highest Mach numbers considered here, the streamwise velocity at the wall exceeds the sound speed, and the flow is supersonic throughout the flow domain.

MW6 123 Performance optimization of an EHD thruster: the influence of secondary emission and the electrodes gap VICTOR H. GRANADOS, PAULO A. SA, *University of Porto* MARIO J. PINHEIRO, *IST - University of Lisbon* We have developed a numerical model to study the performance (thrust, maximum output velocity of the fluid and thrust-to-power ratio) of a single-stage electrohydrodynamic (EHD) thruster with a rod anode and a funnel-like cathode configuration. The electrohydrodynamic processes embody interlocking aspects of non-compressible gas dynamics (Navier-Stokes equations), ionized gas physics, self-consistent accelerating electric field adequately described by Poisson equation and migration of charged particles in an electric field in the drift-diffusion approximation. We considered the following neutral and ionized nitrogen species as the working media: N, N^+, N_2, N_2^+, and N_4^+. In order to optimize the thruster performance, we present two studies: i) a sweeping of the gap between electrodes in order to detect the optimal distance for the proposed model; and ii) a study of the influence of the secondary electron emission coefficient, γ_i, on the discharge mechanism, as γ_i relies on the material used to build the cathode. The working pressure employed in the simulations is 10 Torr (1.3 kPa) and the gas temperature is 300 K.

MW6 124 Spatially resolved optical-emission spectroscopy of a radio-frequency driven iodine plasma source* JAMES DEDRICK, SCOTT DOYLE, *York Plasma Institute, Department of Physics, University of York, Heslington, YO10 5DQ, UK* PASCALINE GRONDEIN, ANE AANESLAND, *Laboratoire de Physique des Plasmas-CNRS, Ecole Polytechnique, 91128 Palaiseau, FR* Iodine is of interest for potential use as a propellant for spacecraft propulsion, and has become attractive as a replacement to xenon due to its similar mass and ionisation potential. Optical emission spectroscopy has been undertaken to characterise the emission from a low-pressure, radio-frequency driven inductively coupled plasma source operating in iodine with respect to axial distance across its transverse magnetic filter. The results are compared with axial profiles of the electron temperature and density for identical source conditions, and the spatial distribution of the emission intensity is observed to be closely correlated with the electron temperature.

*This work has been done within the LABEX Plas@Par project, and received financial state aid managed by the "Agence Nationale de la Recherche", as part of the "Programme d'Investissements d'Avenir" under the reference ANR-11-IDEX-0004-02.

MW6 125 The effect of tailored voltage waveforms on neutral gas heating in a radio-frequency driven electrothermal microthruster SCOTT DOYLE, *York Plasma Institute, Department of Physics, University of York, Heslington, YO10 5DQ, UK* ANDREW GIBSON, *Laboratoire de Physique des Plasmas-CNRS, Ecole Polytechnique, 91128 Palaiseau, FR* RODERICK BOSWELL, CHRISTINE CHARLES, *Space Plasma, Power and Propulsion Laboratory, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 2601, Aus* JAMES DEDRICK, *York Plasma Institute, Department of Physics, University of York, Heslington, YO10 5DQ, UK* Over the past few decades there has been a growing interest in the development compact sources of electric propulsion. In this study the effect of driving the 'Pocket Rocket' radio-frequency electrothermal microthruster with non-sinusoidal voltage waveforms, consisting of multiple harmonics of 13.56 MHz, is investigated using the Hybrid Plasma Equipment Model (HPEM). The results are compared to previous experiments and simulation results using CFD-ACE+ to investigate the potential to generate an increased neutral gas temperature and density in the source. The authors gratefully acknowledge M. Kushner of the University of Michigan for the use of the Hybrid Plasma Equipment Model (HPEM).

MW6 126 Neutral-depletion-induced asymmetric plasma density profile and momentum transport in a helicon thruster* KAZUNORI TAKAHASHI, *Tohoku Univ* YOSHINORI TAKAO, *Yokohama National Univ* AIKI CHIBA, AKIRA ANDO, *Tohoku Univ* Axial momentum lost to a lateral wall of a helicon source is directly measured by using a pendulum force balance, where only the lateral wall is attached to the balance immersed in 60-cm-diam and 1.4-m-long vacuum tank (pumping speed of 300-400 L/s). When operating the source with highly ionized krypton and xenon, the strong density decay along the axis is observed inside the source tube, which seems to be due to the neutral depletion. Under such a condition, a non-negligible loss of the axial momentum to the lateral wall is detected. The presently detected loss of the axial momentum indicates the presence of the ions which are axially accelerated by the electric field in the plasma core and then lost to the lateral wall. Furthermore, the helicon thruster immersed in 1-m-diam and 2-m-long vacuum tank (pumping speed of 4000-5000 L/s) is operated at high rf power up to 5 kW in argon, to demonstrate the neutral-depletion-induced axially asymmetric density profile. Combination between the Langmuir probe and the optical diagnosis indicates that the neutral density at the axial center of the source is reduced to 20% of the initial neutral density.

*This work is partially supported by grant-in-aid for scientific research (16H04084 and 26247096) from the Japan Society for the Promotion of Science.

MW6 127 Effect of High Z material on the performance of an air-breathing laser ablation thruster KOHEI SHIMAMURA, INORU KIYONO, IPPEI YOKOTA, NAOTO OZAKI, SHIGERU YOKOTA, *University of Tsukuba* A Laser propulsion, such as a Lightcraft, is a candidate for the low cost transportation system between the ground to space instead of the chemical rocket. Using the shock wave induced by focusing laser beam on the ablator in air, the huge fuel is unnecessary to generate the thrust. In this study, the high-Z material was doped into the polystyrene to emphasize the ionization effect in air. We evaluate the intensity of the bremsstrahlung radiation, the plasma parameter, and the thrust performance.

MW6 128 Generation of composite Au/TiO_2 nanoparticles by pulsed laser ablation in aqueous media SHOTA KAWAI, MARDIANSYAH MARDIS, NORIHARU TAKADA, WAHYU DIONO, HIDEKI KANDA, MOTONOBU GOTO, *Nagoya Univ* GOTO LAB. TEAM — Composite nanoparticles have been known for their potential applications in photocatalysis, medical and optical limiters. In particular, Au/TiO_2 composite nanoparticles have attracted attention because of its remarkable properties. However, commonly Au/TiO_2 composite nanoparticles are synthesized by chemical method using toxic precursor and reducing agents, and problems by their residue arised. Here, we examined a new synthesis method of composite nanoparticles by pulsed laser ablation (PLA) without any chemical agents, but only with distilled water. Au/TiO_2 composite nanoparticles were obtained by PLA of Ti plate covered with Au and TiO_2 nanoparticles, which were preliminarily synthesized by PLA in distilled water. The synthesized nanoparticles were characterized by using TEM, UV-vis absorption spectroscopy, dynamic light scattering and XRD. The TEM images showed that composite nanoparticles including Au-TiO_2 core-shell nanoparticles were successfully generated with diameter around 100 nm.

MW6 129 Spectroscopic studies of plasma in a carbon arc discharge for synthesis of nanomaterials* VLADISLAV VEKSELMAN, *Princeton Plasma Physics Laboratory* MATTHEW FEURER, *Seton Hall University* YAO-WEN YEH, BRENTLEY STRATTON, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* LABORATORY FOR PLASMA NANOSYNTHESIS TEAM — An atmospheric pressure arc discharge with graphite electrodes is commonly used for synthesis of carbon nanomaterials such as buckyballs, nanotubes and graphene. In operation, the graphite anode ablates providing a feedstock material for synthesis these carbon nanostructures. Existing models [1] predict that nucleation and growth of these nanomaterials in an arc discharge are governed by spatial distributions of density and temperature of plasma species. Control of these distributions can potentially enable optimization of nanosynthesis processes, to achieve the best combination of synthesis selectivity at the synthesis yield. In this work, we report first detail measurements of spatial distribution of arc plasma parameters obtained with a set of in-situ diagnostics, including optical emission spectroscopy and fast framing imaging. These parameters were measured in low- and high- anode ablation modes [2]. Results of these measurements demonstrate a strong correlation between arc plasma and synthesis processes.

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

[1]M. Keidar, A. Shashurin, O. Volotskova, Y. Raitses, and I. I. Beilis, Phys. Plasmas **17**, 057101 (2010).
[2]J. Ng and Y. Raitses, J. Appl. Phys. **117** (2015).

MW6 130 Synthesis of Copper and Nickel Nanoparticles from a Plasma Discharge in Liquid JINYOUNG HUH, SUKHWAL MA, KANGIL KIM, YONG CHEOL HONG, *National Fusion Research Institute* NATIONAL FUSION RESEARCH INSTITUTE TEAM, KWANGWOON UNIVERSITY TEAM, CHONBUK NATIONAL UNIVERSITY TEAM, NPAC TEAM — Nanoscale metal particles have been attracting much attention because of their unique size- and dimensionality dependent physical and chemical properties. In order to fabricate metal nano-particles, many methods are ported such as chemical vapor deposition, thermal decomposition, micro-emulsion, UV-irradiation, the polyol process, and so on. However, previous methods may cause secondary environment pollution. Moreover, most of the synthetic methods are not economically feasible due to low throughput and poor scalability. In this work, we propose the synthesis methods of metal nano-particles by underwater discharge to overcome the shortcomings of reported methods. The copper and nickel nano-particles are synthesized by underwater discharge, and they have the diameter less than 100 nm. Also, we confirmed Cu and Ni nanoparticles were not oxidized through XRD analysis. We expect that the metal nano-particles synthesized by underwater discharge can be applied to electronic industry such as printed electronics and multi-layer ceramic capacitors (MLCCs).

MW6 131 Surface diffusion of a carbon adatom on charged SWCNT* LONGTAO HAN, PREDRAG KRSTIC, *State Univ of NY- Stony Brook* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory* — Diffusion of a carbon adatom on SWCNT could be a mechanism for a CNT growth in a volume plasma, supplementing its growth from a transition metal catalyst nanoparticle. However, being embedded in plasma, the nanotube can charge by the plasma particles irradiation, in particular by electrons. Using Density Functional Theory, Nudged Elastic Band and Kinetic Monte Carlo methods we find (1) equilibrium sites, (2) adsorption energies, (3) potential barriers, (4) vibrational frequencies and (5) most probable pathways for diffusion of the adatom on external surfaces of SWCNTs of (5,5), (10,0) and (10,5) chirality, as function of its charge. The metal (5,5) SWCNT can support a fast diffusion of the carbon adatom, which is accelerated by the presence of the SWCNT negative charge. Reduced model of SWCNT growth is proposed.

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

MW6 132 Synthesis of epitaxially grown core/shell nanocrystals with nonthermal plasmas* KATHARINE HUNTER, JACOB HELD, ANDRE MKHOYAN, UWE KORTSHAGEN, *University of Minnesota* — Nonthermal plasmas have gained increasing adoption as capable sources of nanocrystal materials that are challenging to grow in solution due to the high synthesis temperatures required. To date, little progress has been made to grow core/shell nanocrystals with nonthermal plasmas. In colloidal synthesis, core/shell structures have proven to be indispensable to improve the optical properties of nanocrystal materials. The epitaxially grown shells terminate surface states on the nanocrystal cores and can be selected to form heterojunctions that confine charge carriers in the core region. Here, we present the nonthermal plasma synthesis of germanium (Ge) nanocrystals with epitaxially grown silicon (Si) shells. Core/shell growth is achieved in a single flow-through plasma reactor by first injecting the core precursor and, after its depletion, injecting the shell precursor further downstream. Electron microscopy studies confirm epitaxial shell growth with minimal intermixing of core and shell material. Due to the lattice mismatch between core and shell, we find that Ge cores are compressively strained, which enables tuning of the Ge band structure via shell thickness. This demonstration of core/shell nanocrystals can be extended to an exciting array of heterostructures.

*This work was supported by the MRSEC program of the U.S. National Science Foundation under grant DMR-1420013.

MW6 133 Application of bipolar gas discharge for water sterilization from *S.aureus* and *E-coli* ANATOLIY TARAN, ANDRIY OKHRIMOVSKYY, PETRO KOMOZYNSKYI, OLEKSANDR KYSLYTSYN, *National Aerospace University* SVITLANA TARAN, NATALIYA FILIMONOVA, *National University of Pharmacy* VIKTOR LESNOY, DARIA ORANSKA, *National Aerospace University* Recently, water treatment by gas discharge above the surface of the liquid has attracted a lot of attention. In most cases, however, the unipolar power source is used. Bipolar pulses of high voltage and current can increases degree of water sterilization from organic compounds, both chemical and bacterial since non equilibrium atmospheric plasma contains not only electrons but also positive and negative ions as well as an excited molecules or atoms and active radicals. Heavy charged particles of both signs, accelerated by bipolar electric field, can easily destroy chemical and biological contaminants in water. To evaluate this phenomenon, high voltage bipolar pulse generator was used. The amplitude of the pulse voltage was approaching value of 200 kV at the discharge ignition. The repetition time was varied from 1 to 14 milliseconds. Current pulse had a shape of a superposition of bipolar pulses with decaying amplitude. Liquid surface was used as a cathode or anode.Two types of contaminants, *S.aureus* and *E.coli*, with was 1.5×10^8 CFU/mL were treated by bipolar high voltage pulse discharge. After 30 minutes of exposition, no contaminants were observed within the water.

MW6 134 Dynamics of turbulent front at the correlation between atmospheric pressure plasma jet & gas flow field MAEDE GHASEMI, HAITAO XU, XUEKAI PEI, XINPEI LU, *Huazhong University of Science and Technology* Among variety of plasma applications, there is significant interest recently in the use of plasma as an actuator in flow control for aerodynamic applications in which the correlation between atmospheric pressure plasma jet (APPJ) and gas flow field is a crucial role. In this contribution, dynamic characterizations of the turbulent flow field in APPj are investigated by focusing on the effect of different parameters of APPJ, such as applied voltage, pulse repetition frequency, gas flow rate, and time duration of the pulse We utilized Schlieren photography and photomultiplier tubes (PMT) as a signal triggering of an intensified charge coupled device (ICCD) and also a high speed camera to examine the formation of the turbulent front and its dynamics. The results reveal that the turbulent front will appear earlier and closer to the tube nozzle by increasing the gas flow rate and applied voltage amplitude. It is found that the pulse time duration and repetition frequency cannot change the dynamics and formation of the turbulent front. Further investigation demonstrated that every pulse can excite one turbulent front which is created in a specific position in a laminar region and propagates downstream and the effect of increasing frequency results in the increasing of the number of turbulent front and expansion of their region of formation.

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MW6 136 Measurements of energetic electrons in a Current-Free Double layer NJAAL GULBRANDSEN, ASHILD FREDRIKSEN, *University of Tromso* In inductively coupled helicon sources, current-free double layers (CFDL) can be formed self-consistently without external current forcing. The CFDLs are evidenced by an ion beam formed as a result of a potential drop between the source and the diffusion chamber. The electrons in the double layer play an important role in balancing the ion beam current, but apart from some observations of electron energy probability functions (EEPFs) by means of Langmuir probes, little information has up to now been obtained about the electron population. By means of an inverted retarding field energy analyzer (RFEA) we have measured for the first time the high-energy part of the electron distribution along the radial direction in the diffusion chamber. In this configuration, the RFEA repeller grid is set to a large positive potential, repelling ions and collecting electrons through the discriminator grid. We find a prominent peak of high-energy electrons up to 60 eV at the footprint of the magnetic field lines emerging from the layer near the wall of the source. This coincides with increased electron temperatures and ion densities at this position. Another small but significant distribution of electrons at energies more than 100 eV are observed within the region of the ion beam itself.

MW6 137 Experimental study of a very high frequency, 162 MHz, segmented electrode, capacitively coupled plasma discharge NISHANT SIRSE, CLEO HARVEY, CEZAR GAMAN, BERT ELLINGBOE, *Dublin City University* Radio-frequency capacitively coupled plasma (CCP) discharge operating at a very high frequency, 30-300 MHz, offers many advantages over standard 13.56 MHz CCP. However, there is a limited flexibility on the choice of driving frequency and substrate size due to plasma non-uniformity caused by the standing wave effect and edge effect. To overcome this issue segmented electrode CCP's are proposed and researched. Despite its numerous advantages the power coupling mechanism and plasma chemistry in this type of discharge are not fully understood due to lack of experimental data. In this paper, we present the experimental study of a segmented electrode, 3x4 tile array (10x10 cm square tile with 1 cm tile-to-tile separation), CCP discharge driven at 162 MHz. We measured plasma uniformity and gas temperature using hairpin probe and optical emission spectroscopy respectively. A homemade RF compensated Langmuir probe is employed to measure the Electron Energy Distribution Function (EEDF) by second harmonic technique. Energy resolved quadrupole mass spectrometer is utilized to measure the ion energy distribution. Discharge/plasma properties are investigated for several operating conditions and for power coupling mode in both washer board and checker board configuration. The experimental results show that the uniform plasma density can be maintained over a large area along with highly non-equilibrium condition to produce unique gas phase plasma chemistry.

MW6 138 Electron and negative ion densities in a CW and pulsed 100 MHz capacitively coupled plasma discharge* NISHANT SIRSE, BERT ELLINGBOE, *Dublin City University* TAKAYOSHI TSUTSUMI, SEKINE MAKOTO, MASARU HORI, *Nagoya University* Capacitively coupled plasma (CCP) discharges operating at a very high frequency, 30 -300 MHz, are becoming very popular now a days due to enhanced plasma processing rates and lower damage to the substrate. This is mainly achieved due to higher plasma densities and lower electron temperature produced at higher driving frequencies. Moreover, pulsing of the discharge system is known to deliver charging-free plasma processes which is highly desirable for high-aspect-ratio plasma etching. In this study, we present electron and negative ion densities in a CW and pulsed 100 MHz CCP discharge produced in O_2 and $Ar/O_2/C_4F_8$ gas mixture. Electron density is determined by the Hairpin probe and negative ion density is determined by the pulse laser photo-detachment combined with Hairpin probe. Photo-detachment is performed at 532, 355 and 266 nm laser wavelengths in order to selectively photodetach different negative ions present in the discharge. Experimental results are presented for several power (100-500 W), pressure (1-10 Pa) conditions and for several duty ratios (25 – 75%) for 1 KHz pulse repetition frequency. In CW O_2 plasma, we observed a similar trend in electron and negative ion density vs power, whereas, in $Ar/O_2/C_4F_8$ gas mixture an opposite trend is observed in electron and negative ion density.

*This publication has emanated from research conducted with the financial support of Science Foundation Ireland under the International Strategic Cooperation Award Grant Number SFI/13/ISCA/2846.

MW6 139 Electron Energy Distribution function in a weakly magnetized expanding helicon plasma discharge NISHANT SIRSE, CLEO HARVEY, CEZAR GAMAN, BERT ELLINGBOE, *Dublin City University* Helicon wave heating is well known to produce high-density plasma source for application in plasma thrusters, plasma processing and many more. Our previous study *(B Ellingboe et al. APS Gaseous Electronics Conference 2015, abstract #KW2.005)* has shown observation of helicon wave in a weakly magnetized inductively coupled plasma source excited by m=0 antenna at 13.56 MHz. In this paper, we investigated the Electron Energy Distribution Function (EEDF) in the same setup by using an RF compensated Langmuir probe. The ac signal superimposition technique (second harmonic technique) is used to determine EEDF. The EEDF is measured for 5-100 mTorr gas pressure, 100 W – 1.5 kW rf power and at different locations in the source chamber, boundary and diffusion chamber. This paper will discuss the change in the shape of EEDF for various heating mode transitions.

MW6 140 Magnetic Field Tailored Annular Hall Thruster with Anode Layer SEUNGHUN LEE, HOLAK KIM, JUNBUM KIM, YOUBONG LIM, WONHO CHOE, *Korea Adv Inst of Sci & Tech* KOREA ADV INST OF SCI & TECH TEAM, KOREA INSTITUTE OF MATERIALS SCIENCE COLLABORATION Plasma propulsion system is one of the key components for advanced missions of satellites as well as deep space exploration. A typical plasma propulsion system is Hall effect thruster that uses crossed electric and magnetic fields to ionize a propellant gas and to accelerate the ionized gas to generate momentum. In Hall thruster plasmas, magnetic field configuration is important due to the fact that electron confinement in the electromagnetic fields affects both plasma and ion beam characteristics as well as thruster performance parameters including thrust, specific impulse, power efficiency, and life time. In this work, development of an anode layer Hall thruster (TAL) with magnetic field tailoring has been attempted. The TAL is possible to keep discharge in 1 to 2 kilovolts of anode voltage, which is useful to obtain high specific impulse. The magnetic field tailoring is used to minimize undesirable heat dissipation and secondary electron emission from the wall surrounding the plasma. We will report 3 W and 200 W thrusters performances measured by a pendulum thrust stand according to the magnetic field configuration. Also, the measured result will be compared with the plasma diagnostics conducted by an angular Faraday probe, a retarding potential analyzer, and a ExB probe.

MW6 141 Influence of wake potential on the propagation of the space-charge wave in a waveguide dusty plasma* YOUNG-DAE JUNG, MYOUNG-JAE LEE, KYU-SUN CHUNG, *Hanyang University* The wake potential effects on the propagation of the space-charge dust ion-acoustic wave are investigated in a cylindrically bounded dusty plasma with the ion flow. The results show that the wake potential would generate the double frequency modes in a cylindrically bounded dusty plasma. It is found that the positive mode of the wave frequency with the root of higher-order is smaller than that with the root of lower-order in intermediate wave number domains. However, the negative mode of the scaled wave frequency with the root of higher-order is found to be greater than that with the root of lower-order. It is found that the influence of order of the root of the Bessel function on the wave frequency of the space-charge dust-ion-acoustic wave in a cylindrically confined dusty plasma decreases with an increase of the propagation wave number. It is also found that the double frequency modes increase with increasing Mach number due to the ion flow in a cylindrical dusty plasma. In addition, it is found that the positive mode of the group velocity decreases with an increase of the scaled radius of the plasma cylinder. However, the negative mode group velocity increases with an increase of the radius of the plasma cylinder.

*The work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MISP) (No. 2016R1A2B4011356).

MW6 142 Synthesis of N-graphene using microwave plasma-based methods* ANA DIAS, ELENA TATAROVA, JULIO HENRIQUES, FRANCISCO DIAS, EDGAR FELIZARDO, *Instituto de Plasmas e Fusao Nuclear, Instituto Superior Tecnico, Universidade de Lisboa, Portugal* MIROSLAV ABRASHEV, *Faculty of Physics, Sofia University, Bulgaria* NENAD BUNDALESKI, *University of Belgrade, Serbia* UROS CVELBAR, *Jozef Stefan Institute, Slovenia* In this work a microwave atmospheric plasma driven by surface waves is used to produce free-standing graphene sheets (FSG). Carbonaceous precursors are injected into a microwave plasma environment, where decomposition processes take place. The transport of plasma generated gas-phase carbon atoms and molecules into colder zones of plasma reactor results in carbon nuclei formation. The main part of the solid carbon is gradually carried from the "hot" plasma zone into the outlet plasma stream where carbon nanostructures assemble and grow. Subsequently, the graphene sheets have been N-doped using a N2-Ar large-scale remote plasma treatment, which consists on placing the FSG on a substrate in a remote zone of the N2-Ar plasma. The samples were treated with different compositions of N2-Ar gas mixtures, while maintaining 1 mbar pressure in the chamber and a power applied of 600 W. The N-doped graphene sheets were characterized by scanning and by high-resolution transmission electron microscopy, X-ray photoelectron spectroscopy and Raman spectroscopy. Plasma characterization was also performed by optical emission spectroscopy.

*Work partially funded by Portuguese FCT - Fundacao para a Ciencia e a Tecnologia, under grant SFRH/BD/52413/2013 (PD-F APPLAuSE).

MW6 143 Magnetic field effect on spoke behaviour* JAROSLAV HNILICA, MARTA SLAPANSKÁ, PETER KLEIN, PETR VASINA, *Masaryk University* The investigations of the non-reactive high power impulse magnetron sputtering (HiPIMS) discharge using high-speed camera imaging, optical emission spectroscopy and electrical probes showed that plasma is not homogeneously distributed over the target surface, but it is concentrated in regions of higher local plasma density called spokes rotating above the erosion racetrack. Magnetic field effect on spoke behaviour was studied by high-speed camera imaging in HiPIMS discharge using 3 inch titanium target. An employed camera enabled us to record two successive images in the same pulse with time delay of 3 μs between them, which allowed us to determine the number of spokes, spoke

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rotation velocity and spoke rotation frequency. The experimental conditions covered pressure range from 0.15 to 5 Pa, discharge current up to 350 A and magnetic fields of 37, 72 and 91 mT. Increase of the magnetic field influenced the number of spokes observed at the same pressure and at the same discharge current. Moreover, the investigation revealed different characteristic spoke shapes depending on the magnetic field strength - both diffusive and triangular shapes were observed for the same target material. The spoke rotation velocity was independent on the magnetic field strength.

*This research has been financially supported by the Czech Science Foundation in frame of the project 15-00863S.

MW6 144 Quantum Cause of Gravity Waves and Dark Matter SHANTILAL GORADIA, *Retired* GORADIA TEAM Per Einstein's theory mass tells space how to curve and space tells mass how to move. How do they tell"? The question boils down to information created by quantum particles blinking ON and OFF analogous to 'Ying and Yang' or some more complex ways that may include dark matter. If not, what creates curvature of space-time? Consciousness, dark matter, quantum physics, uncertainty principle, constants of nature like strong coupling, fine structure constant, cosmological constant introduced by Einstein, information, gravitation etc. are fundamentally consequences of that ONE TOE. Vedic philosophers, who impressed Schrodinger so much, called it ATMA split in the categories of AnuAtma (particle soul), JivAtma (life soul) and ParamAtma (Omnipresent soul) which we relate to quantum physics, biology and cosmology. There is no separate TOE for any one thing. The long range relativistic propagations of the strong and weak couplings of the microscopic black holes in [1] are just gravity waves. What else could they be?

[1]Dark Matter from Our Probabilis- tic Gravity, J. Phys. Sci. Appl. 5, 373 (2015) doi:10.17265/2159-5348/2015.008.

MW6 145 Magnetic field effect on spoke behaviour* JAROSLAV HNILICA, MARTA SLAPANSKA, PETER KLEIN, PETR VASINA, *Department of Physical Electronics, Masaryk University, Kotlarska 2, CZ-61137, Brno, Czech Republic* The investigations of the non-reactive high power impulse magnetron sputtering (HiPIMS) discharge using high-speed camera imaging, optical emission spectroscopy and electrical probes showed that plasma is not homogeneously distributed over the target surface, but it is concentrated in regions of higher local plasma density called spokes rotating above the erosion racetrack. Magnetic field effect on spoke behaviour was studied by high-speed camera imaging in HiPIMS discharge using 3 inch titanium target. An employed camera enabled us to record two successive images in the same pulse with time delay of 3 μs between them, which allowed us to determine the number of spokes, spoke rotation velocity and spoke rotation frequency. The experimental conditions covered pressure range from 0.15 to 5 Pa, discharge current up to 350 A and magnetic fields of 37, 72 and 91 mT. Increase of the magnetic field influenced the number of spokes observed at the same pressure and at the same discharge current. Moreover, the investigation revealed different characteristic spoke shapes depending on the magnetic field strength - both diffusive and triangular shapes were observed for the same target material. The spoke rotation velocity was independent on the magnetic field strength.

*This research has been financially supported by the Czech Science Foundation in frame of the project 15-00863S.

MW6 146 Secondary electron emission in the limit of low incident electron energies ALEKSANDR MUSTAFAEV, *St.Petersburg Mining University, Russia* IGOR KAGANOVICH, *Prienceton Plasma Physics Laboratory, USA* VLADIMIR SOUKHOMLINOV, *St.Petersburg State University, Russia* ARTIOM GRABOVSKIY, *St.Petersburg Mining University, Russia* A detailed review of experimental and theoretical studies of secondary electron emission (SEE) at low incident electron energies has been recently given in paper [1]. In particularly, discussion of some authors' statement [2,3] on increase of the SEE yield up to unity if the primary electron energy tends to zero was reviewed. Present paper considers a technique for measurements of SEE yield near a sample surface [4] making use of a magnetic field parallel to the surface. Using this technique it was shown that the SEE yield can approach unity for a polycrystalline, but not for a monocrystalline sample. This result was explained by additional reflection of primary electrons from a potential barrier near the sample surface. Therefore for suppression of the deleterious effects of SEE, e.g, for better performance of accelerators, it is important to monitor and control micro electric-fields arising near a polycrystalline surface.

[1]A. N. Andronov, St. Petersburg State Polytechnic. Univ. J. Phys. Math. Sci. 1, 67 (2014).
[2]R. Cimino *et al.*, Proceedings of IPAC Dresden, Germany 2014.
[3]J. Cazaux, J. Appl. Phys. **111**, 064903 (2012).
[4]A. Mustafaev, I. Kaganovich *et al.*, Bull. APS. **60**, 40 (2015).

MW6 147 An analytical model of multi-component single frequency capacitively coupled plasma and experimental validation* PARTHA SAIKIA, HEMAN BHUYAN, MARIO FAVRE, EDMUND WYNDHAM, FELIPE VELOSO, *Facultad Fisica, Pontificia Universidad Catolica de Chile, Ave. Vicuña Mackena 4860, Santiago 22, Chile* An analytical model describing the hydrogen added argon capacitively coupled plasma (CPP) is pesented and its predictions are tested with the experimental results. In the analytical model, it is found that the radio frequency (rf) current density, electron temperature and density, as well as the density of ion in multi-component plasma collectively influence the normalized sheath potential and thickness. As for low pressure rf plasma, the sheath potential is the qualitative measure of the DC self bias, the trend of variation of DC self bias with hydrogen addition is predicted in this model. The behavior of single frequency multi-component CPP is experimentally studied by a homogeneous discharge model using discharge parameters. In the experiment with hydrogen added argon plasma, the rf power as well as the working pressures are varied. The addition of hydrogen to the argon discharge leads to a decrease of electron density and DC self bias. It also results an increase of electron temperature. Agreements of the experimental results with theoretical predictions are obtained at different experimental conditions. The results obtained in this investigation could be useful for reproducibility, consistency and understanding of a particular processing application.

*Authors acknowledge FONDECYT grant 3160179 and 1130228. Additional funding from Conicyt PIA program ACT1108 is also acknowledged.

MW6 148 An analytical model of multi-component single frequency capacitively coupled plasma and experimental validation* PARTHA SAIKIA, HEMAN BHUYAN, MARIO FAVRE, EDMUND WYNDHAM, FELIPE VELOSO, *Facultad Fisica, Pontificia Universidad Catolica de Chile, Ave. VicuÃ±a Mackena 4860, Santiago 22, Chile* An analytical model describing the hydrogen added argon capacitively coupled plasma (CPP) is pesented and its predictions are tested with the experimental results. In the analytical model, it is found that the radio frequency (rf) current density, electron temperature and density, as well as the density of ion in multi-component plasma collectively influence the normalized sheath potential and thickness. As for low pressure rf plasma, the sheath potential is the qualitative measure of the DC self bias, the trend of variation of DC self bias with hydrogen addition is predicted in this model. The behavior of single frequency multi-component CPP is experimentally studied by a homogeneous discharge model using discharge parameters. In the experiment with hydrogen added argon plasma, the rf power as well as the working pressures are varied. The addition of hydrogen to the argon discharge leads to a decrease of electron density and DC self bias. It also results an increase of electron temperature. Agreements of the experimental results with theoretical predictions are obtained at different experimental conditions.

*Authors acknowledge FONDECYT grant 3160179 and 1130228.

MW6 149 2D probe diagnostics of anisotropic plasmas with no velocity space symmetry ALEKSANDR MUSTAFAEV, *St.Petersburg Mining University, Russia* VLADIMIR SOUKHOMLINOV, *St.Petersburg State University, Russia* ARTIOM GRABOVSKIY, OSCAR MURILLO, SOFIA PODENKO, *St.Petersburg Mining University, Russia* This paper is devoted to the development of the probe method used for analysis of non-equilibrium anisotropic plasmas. The probe method for determination of full electron and ion velocity distribution functions (EVDF) in axially symmetric plasmas was theoretically and experimentally approved [1,2]. To recover the full EVDF to the Legendre polynomials of order N it is necessary to measure the second derivative of probe current I''_U in probe's N different orientations. In [3] there are the theoretical principles of the EVDF recovering method for plasmas with no velocity space symmetry. To determine the full EVFD with the same degree of accuracy it is necessary to measure I''_U in flat probe's N [2] orientations. This paper gives further development of probe method. While restoring the full EVDF in plasma objects with bilateral symmetry it became possible to reduce the number of the probe's angular orientations by two. It opens up new possibilities to obtain new information about Langmuir paradox in plasma [4].

[1]A. S. Mustafaev *et al.*, London: Plenum Press. **367**, 531 (1998).
[2]A. S. Mustafaev, V. S. Soukhomlinov *et al.*, Techn. Phys. **60**, 1778 (2015).
[3]C. R. Woods and I. Sudit, Phys. Rev. **50**, 222 (1994).
[4]V. Godyak *et al.*, Plasma Sour. Sci. Techn. **24**, 052001 (2015).

MW6 150 Photoionization sensors for non-invasive medical diagnostics* ALEKSANDR MUSTAFAEV, *St.Petersburg Mining University, Russia* IULIIA RASTVOROVA, KRISTINA KHOBNYA, SOFIA PODENKO, *St. Petersburg Mining University, Russia* The analysis of biomarkers can help to identify the significant number of diseases: lung cancer, tuberculosis, diabetes, high levels of stress, psychosomatic disorders etc. To implement continuous monitoring of the state of human health, compact VUV photoionization detector with current-voltage measurement is designed by Saint-Petersburg Mining University Plasma Research Group. This sensor is based on the patented method of stabilization of electric parameters – CES (Collisional Electron Spectroscopy). During the operation at atmospheric pressure VUV photoionization sensor measures the energy of electrons, produced in the ionization with the resonance photons, whose wavelength situated in the vacuum ultraviolet (VUV). A special software was developed to obtain the second-order derivative of the I–U characteristics, taken by the VUV sensor, to construct the energy spectra of the characteristic electrons. VUV photoionization detector has an unique set of parameters: small size (10*10*1 mm), low cost, wide range of recognizable molecules, as well as accuracy, sufficient for using this instrument for the medical purposes. This device can be used for non-invasive medical diagnostics without compromising the quality of life, for control of environment and human life.

*Work supported by Foundation for Assistance to Small Innovative Enterprises in Science and Technology.

MW6 151 Modeling of plasma in a hybrid electric propulsion for small satellites MANISH JUGROOT, ALEX CHRISTOU, *Royal Military College of Canada* As space flight becomes more available and reliable, space-based technology is allowing for smaller and more cost-effective satellites to be produced. Working in large swarms, many small satellites can provide additional capabilities while reducing risk. These satellites require efficient, long term propulsion for manoeuvres, orbit maintenance and de-orbiting. The high exhaust velocity and propellant efficiency of electric propulsion makes it ideally suited for low thrust missions. The two dominant types of electric propulsion, namely ion thrusters and Hall thrusters, excel in different mission types. In this work, a novel electric hybrid propulsion design is modelled to enhance understanding of key phenomena and evaluate performance. Specifically, the modelled hybrid thruster seeks to overcome issues with existing Ion and Hall thruster designs. Scaling issues and optimization of the design will be discussed and will investigate a conceptual design of a hybrid spacecraft plasma engine.

MW6 152 Multiply charged ion generation according to magnetic field configurations in Hall thruster plasmas* HOLAK KIM, SEUNGHUN LEE, JUNBUM KIM, YOUBONG LIM, WONHO CHOE, *Korea Adv Inst of Sci & Tech* KIMS COLLABORATION Plasma propulsion is the most promising techniques to operate satellites for low earth orbit as well as deep space exploration. A typical plasma propulsion system is Hall thruster (HT) that uses crossed electromagnetic fields to ionize a propellant gas and to accelerate the ionized gas. In HT the tailoring of magnetic fields is significant due to that the electron confinement in the electromagnetic fields affects thruster performances such as thrust force, specific impulse, power efficiency, and life time. We designed an anode layer HT (TAL) with the magnetic field tailoring. The TAL is possible to keep discharge in 1~2 kilovolts, which voltage is useful to obtain high specific impulse The magnetic field tailoring is adapted to minimize undesirable heat dissipations and secondary electron emissions at a wall surrounding plasma In presentation, we will report TAL performances including thrust force, specific impulse, and anode efficiency measured by a pendulum thrust stand. This mechanical measurement will be compared to the plasma diagnostics conducted by angular Faraday probe, retarding potential analyzer, and ExB probe

*Grant No. 2014M1A3A3A02034510.

MW6 153 Magnetic Field Tailored Annular Hall Thruster with Anode Layer SEUNGHUN LEE, HOLAK KIM, JUNBUM KIM, YOUBONG LIM, WONHO CHOE, *Korea Adv Inst of Sci & Tech* KOREA INSTITUTE OF MATERIALS SCIENCE COLLABORATION Plasma propulsion system is one of the key components for advanced missions of satellites as well as deep space exploration. A typical plasma propulsion system is Hall effect thruster that uses crossed electric and magnetic fields to ionize a propellant gas and to accelerate the ionized gas to generate momentum. In Hall thruster plasmas, magnetic field configuration is important due to the fact that electron confinement in the electromagnetic fields affects both plasma and ion beam characteristics as well as thruster performance parameters including thrust, specific impulse, power efficiency, and life time. In this work, development of an anode layer Hall thruster (TAL) with magnetic field tailoring has been attempted. The TAL is possible to keep discharge in 1 to 2 kilovolts of anode voltage, which is useful to obtain high specific impulse. The magnetic field tailoring is used to minimize undesirable heat dissipation and secondary electron emission from the wall surrounding the plasma. We will report 3 W and 200 W thrusters performances measured by a pendulum thrust stand according to the magnetic field configuration. Also, the measured result will be compared with the plasma diagnostics conducted by an angular Faraday probe, a retarding potential analyzer, and a ExB probe.

MW6 154 Affect of an electrostatic wave on optical pumping* FREDERICK SKIFF, *Univ of Iowa* FENG CHU, *University of Iowa* Extensive information can be obtained on wave-particle interactions and wave fields by direct measurement of perturbed ion distribution functions using laser-induced fluorescence (LIF). For practical purposes, LIF is normally performed on metastable states – here we consider singly ionized Argon in an inductively coupled plasma. Wave detection is best performed using phase-coherent detection, but power spectra can be obtained through correlation functions. If laser intensity is increased to obtain a better LIF signal, then the effects of optical pumping will produce systematic effects depending on the collision rates which control metastable population and lifetime. We simulate the wave-detection process using a Lagrangian model for the LIF signal. This approach separates the classical dynamics of the ion orbits from the quantum-state transitions produced by optical pumping. The two dynamics nevertheless become coupled in the presence of an electrostatic wave. The numerical simulation is compared with experimental data from a CW magnetized plasma discharge with externally launched ion acoustic waves.

*Work supported by US DOE DE-FG02ER54543.

SESSION NW1: LASER-BASED DIAGNOSTICS I

Wednesday Afternoon, 12 October 2016; Room: 1 at 15:00; Tsuyohito Ito, Osaka University, presiding

Invited Papers

15:00

NW1 1 Development and application of laser-collision induced fluorescence for studying dynamic and structured plasmas*
EDWARD BARNAT, *Sandia National Laboratories*

Laser collision-induced fluorescence (LCIF) is a powerful diagnostic which can be used for making temporally and spatially resolved measurements of electron densities in a plasma discharge. The technique, which involves the measurement of optical emission emanating from higher energy excited states due to the redistribution of the lower energy laser-excited state by collisions with energetic plasma species, has been readily employed to study both helium and argon discharges. In this presentation, an overview of the fundamental principles and anticipated limitations of the LCIF method will be presented. Examples of the LCIF method applied to structured and dynamic discharges generated in helium and argon will be presented to demonstrate the utility of this diagnostic technique. Finally, recent efforts used to extend the LCIF method to higher pressure (near atmospheric pressure) discharges will be discussed.

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

Contributed Papers

15:30

NW1 2 Detection of beam-crossing Doppler shift using an optical vortex beam* MITSUTOSHI ARAMAKI, *Nihon University* SHINJI YOSHIMURA, *National Institute for Fusion Science* YASUNORI TODA, *Hokkaido University* TOMOHIRO MORISAKI, *National Institute for Fusion Science* KENICHIRO TERASAKA, MASAYOSHI TANAKA, *Kyushu University* Optical vortex (OV) beams are a set of solutions of the paraxial Helmholtz equation in the cylindrical coordinates, and its wave front has a spiral shape. The observer in the OV beam feels a three-dimensional Doppler effect, since the OV beam has the three-dimensional spiral wave front. We intend to improve the flexibility of the traditional Doppler spectroscopy using the OV beam. Since the multi-dimensional Doppler shifts are mixed into a single Doppler spectrum, we performed a modified saturated absorption spectroscopy to separate the Doppler components. The OV and plane wave are used as a probe beam and pump beam, respectively. The three-dimensional OV-beam's Doppler shifts define a tilted excitation volume in the velocity space. Therefore, the excitation volume of the plane-wave pump beam slices the tilted excitation volume of the OV beam. Since the configuration of the excitation volume depends on the location in the beam cross-section, the excitation volumes in the velocity space is mapped in the beam cross-section. The beam-crossing Doppler shift was observed as a local absorption dip in the probe-beam cross-section. The detail of optical vortex spectroscopy will be discussed in the presentation.

*This study was partially supported by JSPS KAKENHI Grand Number 25287152.

15:45

NW1 3 High Sensitive Temperature Measurement of Microwave Plasma using Wavelength Modulation Spectroscopy TOHRU YAMADA, MAKOTO MATSUI, TAITO KAWAKAMI, *Shizuoka University* Translational temperature is one of the key parameter to evaluate plasma conditions. In this study, we propose a novel method to determine the temperature using wavelength modulation spectroscopy. The peak value of second harmonic signal was measured as a function of the modulation depth. The translational temperature was estimated by fitting theoretically calculated curve to the characteristic curve. As a result of microwave argon discharge plasma, the estimated temperature shows good agreement with that measured by laser absorption spectroscopy using microwave argon plasma in the pressure range from 9.3 Pa to 446 Pa.

16:00

NW1 4 Spatiotemporal Evolution of Ar($^3P_2$) Metastable Density Generated in a Pulsed DC Atmospheric Pressure micro-Plasma Jet Impinging on a Glass Plate K. GAZELI, G. BAUVILLE, ET-T. ES-SEBBAR, M. FLEURY, O. NEVEAU, ST. PASQUIERS, J. SANTOS SOUSA, *LPGP, CNRS, Univ. Paris-Sud, Universite Paris-Saclay, 91405 Orsay, France* LABORATOIRE DE PHYSIQUE DES GAZ ET DES PLASMAS TEAM Atmospheric Pressure micro-Plasma Jets (APPJs) are promising tools in various domains such as biomedical and material treatments. In this work, APPJs are produced in pure argon at variable flow rates (i.e., 200, 400 and 600 sccm), by applying high voltage positive pulses (250 ns in FWHM and 6 kV in amplitude) at a repetition frequency of 20 kHz. The generated plasma impacts an ungrounded glass plate placed at a distance of 5 mm from the tube's orifice and perpendicular to the streamers propagation. At these conditions, a diffuse discharge is established resulting in a non-filamentary and reproducible plasma, in contrast with the free-jet case (no target). This allows the quantification of the absolute density of the Ar($1s_5$) metastable state by using laser absorption spectroscopy to probe the transition $1s_5 \rightarrow 2p_9$ at 811.531 nm. The experiments show the dependence on the gas flow rate and on the axial and radial positions of the maximum density (6-9x10^{13} cm^{-3}). At 200 sccm, it is obtained close to the tube's orifice, while with increasing flow rate it is displaced towards the plate. Regarding the radial variation, density maxima are obtained in a small area around the streamers propagation axis.

16:15

NW1 5 Cavity-enhanced absorption spectroscopy to characterize atmospheric pressure plasma jets JEAN-PIERRE VAN HELDEN, ANDY NAVE, STEPHAN REUTER, JUERGEN ROEPCKE, *INP Greifswald, Germany* MICHELE GIANELLA, GRANT RITCHIE, *Department of Chemistry, Physical and Theoretical Chemistry Laboratory, University of Oxford, United Kingdom* Non-equilibrium atmospheric pressure plasma jets gain more and more interest as their technological applications increase in diverse fields such as material processing and plasma medicine. Hence, it is essential to diagnose the fluxes of the species generated by these plasma sources to identify relevant fundamental processes and to improve process efficiency. Especially for a comprehensive understanding of the kinetics of the transient species involved, high precision measurements of reactive molecular precursors, free radicals and to identify of any short lived species are of crucial importance. However, the detection of transient species in these type of plasmas poses a challenge for diagnostic techniques as the plasmas typically have small dimensions and high density gradients in space and time. We have overcome these limitations by using cavity-enhanced absorption spectroscopy (CEAS). In this contribution, the latest results concerning the detection of transient species in two types of plasma jets employing CEAS in the near- and mid-infrared spectral range will be presented. We will show that with these methods spatially resolved investigations of concentrations in the mm sized effluent of the plasma jet can be achieved.

16:30

NW1 6 An improved model to analyze Langmuir probe assisted photo-detachment signal for measuring electronegative plasma parameters* NISHANT SIRSE, *NCPST and School of Physical Sciences, Dublin City Univ* NOUREDDINE OUDINI, *Laboratoire des plasmas de décharges, Centre de Dévelopement des Technologies Avancées, Algiers, Algeria* ABDERREZEG BENDIB, *Laboratoire d'Electronique Quantique, Faculté de Physique, USTHB, Algiers, Algeria* ALBERT R ELLINGBOE, *NCPST and School of Physical Sciences, Dublin City Univ, Ireland* A diagnostic technique for measuring negative ion parameters based on Langmuir probe assisted laser photo-detachment relies on a theoretical model which relates the rise in the electron saturation current to electronegativity in the plasma. The existing model depend on various assumptions and neglect electrostatic potential barrier formed between the laser column (electropositive column) and the surrounding electronegative plasma in order to prevent the outward flow of electrons from the electropositive plasma column. These assumptions leads to erroneous estimation of the plasma electronegativity. In the present work, we present an analytical model to analyze Langmuir probe assisted photo-detachment signal in order to improve the accuracy of measured electronegativity and extended this technique for measuring electron temperature and charged species density. The analytical model is validated using both experiments and particle-in-cell simulation. The results shows improved accuracy in the measured parameters when compared to existing model.

*This work was supported by the Korea Institute for the Advancement of Technology and Ministry of Knowledge Economy (L-2010-1438-000), Republic of Korea, Enterprise Ireland and the European Regional Development Fund (ERDF) under NSRF 2007-2013.

16:45

NW1 7 Real-time monitoring of reactive species in downstream etch reactor by VUV broad-band absorption spectroscopy R. SORIANO, L. VALLIER, G. CUNGE, N. SADEGHI, *LTM, Univ. Grenoble & CNRS* Plasma etching of nanometric size, high aspect-ratio structures is more challenging at each new technological node. Remote plasmas are beginning to find use when damages on nanostructures by ion bombardment become critical or when etching with high selectivity on different materials present on the wafer is necessary (*i.e.* tungsten oxide etching with fluorine and hydrogen containing plasmas in remote reactor from AMAT). Furthermore, it is expected that downstream plasma will replace many wet chemical etching processes to alleviate the issue of pattern collapses caused by capillary forces when nanometer size high aspect ratio structures are immersed in liquids. In these downstream plasmas, radicals are the main active species and a control of their density is of prime importance. Most of gases used and radicals produced in etching plasmas (HBr, BrCl, Br_2, NF_3, CH_2F_2,. . .) have strong absorption bands in the vacuum UV spectral region and we have shown that very low concentration of these species can be detected by VUV absorption [1]. We have recently improved the technique by using a VUV CCD camera, instead of the PMT, which render possible the Broad-Band absorption spectroscopy in the 120-200 nm range, with a deuterium lamp, or a laser produced xenon arc lamp as light source. The multi-spectral detection ability of the CCD reduces the acquisition time to less than 1 second and can permit the real time control of the process control.

[1]G. Cunge *et al.*, J. Phys. D: Appl. Phys. **44**, 122001 (2011).

SESSION NW2: PLASMA ETCHING

Wednesday Afternoon, 12 October 2016; Room: 2a at 15:00; Pascal Chabert, Ecole Polytechnique, presiding

Invited Papers

15:00

NW2 1 Layer by layer etching of $LaAlSiO_x$

HISATAKA HAYASHI, *Toshiba corporation*

In order to fabricate a gate transistor with high-k oxide materials, removal of high-k oxide films after gate electrode etching is necessary for the formation of ohmic contacts on source and drain regions. It is crucial that the removal process of high-k oxide film by dry etching is highly selective to and low in damage to the Si substrate in order to avoid the degradation of device performances. Sasaki et al. have achieved a high $LaAlSiO_x$-to-Si selectivity of 6.7 using $C_4F_8/Ar/H_2$ plasma [1]. In the $LaAlSiO_x$ etching process using $C_4F_8/Ar/H_2$ plasma, H_2 plays a role in breaking the metal-oxygen bond to enhance etching of $LaAlSiO_x$ [1]. Based on this result, the process was decomposed into two steps: a surface modification step using H_2 plasma to break the metal-oxygen bond, and a removal step using C_4F_8/Ar plasma. A sequential layer by layer etching could realize low damage etching, similar to atomic layer etching. Therefore, a sequential $LaAlSiO_x$ etching process using a H_2 surface modification step followed by a removal step using C_4F_8/Ar plasma is investigated. Experiments were carried out on 300 mm diameter wafers using the 100/13.56 MHz dual frequency superimposed capacitively coupled plasma reactor. The etching gases were H_2 and C_4F_8/Ar for each step, respectively. Plasma process conditions were 100 MHz power of 1000 W (plasma generation), 13.56MHz power varied from 0 W to 300W (ion energy control). The substrate temperature was 40 Â°C. 15nm thick $LaAlSiO_x$ blanket film was used for evaluation of the etched amount. Film thickness was measured by X-ray fluorescent analysis thickness meter before and after plasma exposure. The etched amount of $LaAlSiO_x$ by the C_4F_8/Ar plasma step doubled with H_2 modification. It is confirmed that when the C_4F_8/Ar plasma treatment time is sufficient to remove the surface modification layer, a self-limiting reaction is realized. Furthermore, it is confirmed that the etched amount per step can be controlled by control of the ion energy of H_2 plasma.

[1]T. Sasaki, K. Matsuda, M. Omura, I. Sakai, and H. Hayashi, Jpn. J. Appl. Phys. **54**, 06GB03 (2015).

Contributed Papers

15:30

NW2 2 Variation in photon-induced interface defects due to transient behavior of pulse modulated inductively coupled plasma Y. MIYOSHI, M. FUKASAWA, K. NAGAHATA, T. TATSUMI, *Sony Semiconductor Solutions Corp.* Z. LIU, Y. ZHANG, A. ANDO, K. TAKEDA, K. ISHIKAWA, M. SEKINE, M. HORI, *Nagoya Univ.* It is important to reduce photon-induced interface defects generated in the plasma process for electronic device performance. In this study, we investigated the effect of transient behavior of a pulse-modulated ICP on these defects. The C-V analysis revealed the pulse frequency (0.5 – 20 KHz) dependence of the interface state density (D_{it}) in the SiN/Si interface whose variation was proportional to the UV fluence from discharge. By increasing the frequency, the D_{it} increased, was a maximum at 10 kHz, and then decreased. The D_{it} was lower than that in the CW at the lower frequencies, but was higher at the higher frequencies (>10 KHz). The transient behavior of the pulse plasma is presumed to be the cause of this property. The time resolved OES revealed that the optical emission overshoot appeared after ignition due to the variation in the electron temperature and number density in the early ON phase. The number of overshoots increased with increasing frequency. Therefore, the UV fluence and the D_{it} were increased. At the higher frequencies, the variation in the electron temperature and number density were suppressed due to the stepwise ionization via long-lived metastable species. Therefore the overshoot amplitude decreased. As a result, the UV fluence and the D_{it} were decreased. The results revealed that control of the transient behavior of pulse-modulated plasma is important to reduce photon-induced defects in the plasma process.

15:45

NW2 3 Computer modelling of cryogenic etching in $SF_6/O_2/SiF_4$ and CxFy inductively coupled plasmas* QUAN-ZHI ZHANG, ANNEMIE BOGAERTS, *University of Antwerp* Plasma etching plays a more and more important role in microchip fabrication, due to its anisotropy during surface processing. However, current state-of-the-art plasma processing faces significant challenges when going beyond 14 nm features, such as plasma induced damage. A novel process with limited plasma damage is cryogenic etching of low-k material with $SF_6/O_2/SiF_4$ and CxFy plasmas. In this work, a hybrid Monte Carlo-fluid model is employed to describe the plasma behavior, including the species and temperature distributions and power deposition, for $SF_6/O_2/SiF_4$ and CxFy gas mixtures, applied for cryogenic etching under various gas ratios and operating conditions, which can help to establish an optimal process window.

*Quan-Zhi Zhang gratefully acknowledges the Marie Sklodowska-Curie Action Individual Fellowships (MSCA-IF-2015-EF).

16:00

NW2 4 Temporal evolution of as-developed line and space photoresist profiles during etch BARTON LANE, PETER VENTZEK, *Tokyo Electron America* ALOK RANJAN, VINAYAK RASTOGI, *TEL Technology Center, America, LLC* JUN YOSHIKAWA, *Tokyo Electron Miyagi, LLC* We discuss here the etching of the as-developed photoresist pattern of lines and spaces. By examining time partition studies of the etching process, we show that the evolution of a photoresist profile has several distinct phases. These are caused by the material properties of the as-developed photoresist polymer, the change in these material properties due to the plasma interaction with the photoresist and to geometric effects caused by the interaction of faceting profiles and finite line widths. By exploiting sheath bending to direct ions into the sidewall of the lines we examine the etch characteristics of the photoresist side walls. Further by comparing wide to narrow lines, and nested to iso lines, we deconvolve the effects of line geometry and the material properties of the photoresist. For these studies pure argon and mixed argon/fluorocarbon chemistries are used.

16:15

NW2 5 Origin of plasma-induced surface roughening and ripple formation during plasma etching KOUICHI ONO, NOBUYA NAKAZAKI, HIROTAKA TSUDA, YOSHINORI TAKAO, KOJI ERIGUCHI, *Kyoto University* Atomic- or nanometer-scale roughness on feature surfaces has become an important issue to be resolved in the fabrication of nanoscale devices. Control of the surface roughening during plasma etching might be possible, given a deeper understanding of plasma-surface interactions concerned with it. We have investigated the origin of plasma-induced surface roughening and ripple formation during plasma etching of silicon in chlorine, based on a comparison of experiments with Monte Carlo-based atomic-scale cellular model simulations for surface feature evolution and classical molecular dynamics simulations for etch fundamentals. The experiments showed two modes of surface roughening which occur depending on ion incident energy: one is the roughening mode, exhibiting an almost linear increase of roughness with time; the other is the smoothing mode, retaining a smooth surface during etching, and smoothing of initially rough surfaces. The experiments also demonstrated the ripple formation in response to ion incidence angle onto substrate surfaces. These results are interpreted in terms of effects of ion reflection from microscopically roughened surfaces on incidence, which depend on incident ion species.

16:30

NW2 6 Tailored Voltage Waveforms in an SF_6/O_2 discharge: slope asymmetry and its effect on surface nanotexturing of silicon* G. FISCHER, *Institut Photovoltaique d'Ile-de-France* E. DRAHI, G. POULAIN, *Total MS-Energie Nouvelles* B. BRUNEAU, E. V. JOHNSON, *LPICM, CNRS, Ecole Polytechnique, Universite Paris-Saclay* The nanotexturing of the surface of a crystalline silicon (c-Si) wafer for improved photovoltaic performance can be achieved through the use of a SF_6/O_2 capacitively coupled reactive ion etching plasma. In this study, we attempt to modify the texturing conditions by taking advantage of slope asymmetries of Tailored Voltage Waveform (TVW) excitation. We show that TVW shapes resembling "sawtooths", presenting a large slope asymmetry, induce high ionization asymmetries in the discharge, and that the dominance of this effect strongly depends on both gas mixture and pressure. These asymmetries have been previously observed in other electronegative gas and are due to differing plasma sheath dynamics at powered and grounded electrode in a discharge operating in drift-ambipolar mode. The texturing of c-Si in SF_6/O_2 occurs through competing mechanisms, including etching by fluorine radicals and in-situ deposition of micro-masking species. The relative fluxes of etching and passivating species are expected to be strongly varied due to the plasma asymmetry. Morphological and optical characterization of textured c-Si surfaces will give more insight into both the plasma properties and the mechanisms involved in dry nanotexturing.

*This project has been supported by the French Government in the frame of the program of investment for the future (Programme d'Investissement d'Avenir - ANR-IEED-002-01).

16:45

NW2 7 Simulation of Plasma Etching PAUL MOROZ, *Tokyo Electron Technology Center, America, LLC* DANIEL MOROZ, *University of Pennsylvavnia* Plasma is an indispensable tool in materials processing. It provides chemically and physically active species and directional flows of energetic species enabling deep etching with good straight profiles required by the industry. At present time, the only feasible methods of simulating the resulting feature profiles are those which fall within the scope of feature-scale (FS) simulation methods, utilizing engineering-type of reactions of incoming species with solid materials. At the same time, the molecule dynamics (MD) methods are emerging as an important alternative approach to simulating extremely small features with sizes below of a few nanometers. In our presentation, we discuss both FS methods implemented into the FPS3D code and MD methods implemented into the MDSS code. We also discuss the ways of extracting information about the reactions and interactions used in FS codes from the MD simulations utilizing the approach of interatomic potentials. For this presentation, we selected two types of simulation cases for etching. The first type considers simulation of mostly etching and implantation, such as during Si etching by chlorine-argon plasma. The second type considers ALE (atomic layer etch) when etching is done by a cyclic process of surface passivation/activation with the following process of etching/removal of a single atomic layer per cycle or per a few cycles, allowing ultimate processing accuracy. The simulations are carried out with both FS and MD codes to provide the data for relation and comparison between those two very different approaches.

SESSION NW3: SURFACE AND DIELECTRIC BARRIER DISCHARGES

Wednesday Afternoon, 12 October 2016
Room: 2b at 15:00
Timo Gans, University of York, presiding

Contributed Papers

15:00

NW3 1 ABSTRACT WITHDRAWN

15:15

NW3 2 Zero dimensional model of atmospheric SMD discharge and afterglow in humid air* RYAN SMITH, EFE KEMANECI, BJOERN OFFERHAUS, KATHARINA STAPELMANN, RALPH PETER BRINKMANN, *Ruhr Universitaet Bochum* A novel mesh-like Surface Micro Discharge (SMD) device designed for surface wound treatment is simulated by multiple time-scaled zero-dimensional models. The chemical dynamics of the discharge are resolved in time at atmospheric pressure in humid conditions. Simulated are the particle densities of electrons, 26 ionic species, and 26 reactive neutral species including: O_3, NO, and HNO_3. The total of 53 described species are constrained by 624 reactions within the simulated plasma discharge volume. The neutral species are allowed to diffuse into a diffusive gas regime which is of primary interest. Two interdependent zero-dimensional models separated by nine orders of magnitude in temporal resolution are used to accomplish this; thereby reducing the computational load. Through variation of control parameters such as: ignition frequency, deposited power density, duty cycle, humidity level, and N_2 content, the ideal operation conditions for the SMD device can be predicted. The described model has been verified by matching simulation parameters and comparing results to that of previous works [1]. Current operating conditions of the experimental mesh-like SMD were matched and results are compared to the simulations.

*Work supported by SFB TR 87.

[1] Sakiyama, J. Phys. D: Appl. Phys. **45**, 425201 (2012).

15:30

NW3 3 Study on the mode-transition of nanosecond-pulsed dielectric barrier discharge between uniform and filamentary by controlling pressures and pulse repetition frequencies SIZHE YU, XINPEI LU, *Huazhong University of Science & Technology* We investigate the temporally resolved evolution of the nanosecond pulsed dielectric barrier discharge (DBD) in a moderate 6mm gap under various pressures and pulse repetition frequencies (PRFs) by intensified charge-coupled device (ICCD) images, using synthetic air and its components oxygen and nitrogen. It is found that the pressures are very different when the DBD mode transits between uniform and filamentary in air, oxygen, and nitrogen. The PRFs can also obviously affect the mode-transition. The transition mechanism in the pulsed DBD is not Townsend-to-streamer, which is dominant in the traditional alternating-voltage DBDs. The pulsed DBD in a uniform mode develops in the form of plane ionization wave, due to overlap of primary avalanches, while the increase in pressure disturbs the overlap and DBD develops in streamer instead, corresponding to the filamentary mode. Increasing the initiatory electron density by pre-ionization methods may contribute to discharge uniformity at higher pressures. We also find that the dependence of uniformity upon PRF is non-monotonic.

15:45

NW3 4 Influence of the gap size and dielectric constant of the packing on the plasma discharge in a packed bed dielectric barrier discharge reactor: a fluid modeling study KOEN VAN LAER, ANNEMIE BOGAERTS, *Plasmant, University of Antwerp* Packed bed dielectric barrier discharge (DBD) reactors have proven to be very useful sources of non-thermal plasma for a wide range of applications, of which the environmental applications have received most attention in recent years. Compared to an empty DBD reactor, a packing was introduced to either enhance the energy efficiency of the process, or, if the packing is catalytically active, steer the process towards a preferred end product. A wide range of geometries, bead sizes and bead materials have been tested experimentally in the past. However, since experimental diagnostics become more difficult with a packing present, a computational study is proposed to gain more insight. Using COMSOL's built in plasma module, a 2D axisymmetric fluid model is developed to study the influence of the gap size and the dielectric constant (ε) of the packing. Helium is used as discharge gas, at atmospheric pressure and room temperature. By decreasing the gas gap, the electric field strength is enhanced, resulting in a higher number of current peaks per half cycle of applied rf potential. Increasing ε also enhances the electric field strength. However, after a certain ε, its influence saturates. The electric field strength will no longer increase, leaving the discharge behavior unchanged.

16:00

NW3 5 Properties Influencing Plasma Discharges in Packed Bed Reactors* JULIUSZ KRUSZELNICKI, KENNETH W. ENGELING, JOHN E. FOSTER, MARK J. KUSHNER, *University of Michigan* Atmospheric pressure dielectric barrier discharges (DBDs) sustained in packed bed reactors (PBRs) are being investigated for CO_2 removal and conversion of waste gases into higher value compounds. We report on results of a computational investigation of PBR-DBD properties using the plasma hydrodynamics simulator *nonPDPSIM* with a comparison to experiments. Dielectric beads (rods in 2D) were inserted between two coplanar electrodes, 1 cm apart filled by humid air. A step-pulse of -30 kV was applied to the top electrode. Material properties of the beads (dielectric constant, secondary emission coefficient) and gas properties (photoionization and photo-absorption cross-sections, temperature) were varied. We found that photoionization plays a critical role in the propagation of the discharge through the PBR, as it serves to seed charges in regions of high electric field. Increasing rates of photo-ionization enable increases in the discharge propagation velocity, ionization rates and production of radicals. A transition between DBD-like and arc-like discharges occurs as the radiation mean free path decreases. Increasing the dielectric constant of the beads increased electric fields in the gas, which translated to increased discharge propagation velocity and charge density until $\varepsilon/\varepsilon_0 \approx 100$. Secondary electron emission coefficient and gas temperature have minimal impacts on the discharge propagation though the latter did affect the production of reactive species.

*Work supported by US DOE Office of Fusion Energy Science and the National Science Foundation.

16:15

NW3 6 Influence of excitation frequency on helium metastable density in atmospheric pressure DBD J-S. BOISVERT, *Univ. Montreal, Canada* N. SADEGHI, *LTM & LIPht, Univ. Grenoble & CNRS, France* J. MARGOT, *Univ. Montreal, Canada* F. MASSINES, *Promes-CNRS, Perpignan, France* Diffuse dielectric barrier discharges in atmospheric-pressure helium was sustained over a wide range of excitation frequencies (50 kHz to 15 MHz). Emission spectroscopy and resonant absorption and laser absorption on He(2^3S) metastable atoms have been used to characterize different plasma regimes, which with increasing frequency changes from a low pressure glow discharge (APGD) to Townsend-like mode (TL) and finally to a continuously sustained plasma. This later can be in Ω mode (with uniform E-field) or RF-α mode (with sheath formation). Depending on applied power, the time-averaged He(2^3S) density remains below 3 10^{16} m^{-3} in TL and Ω modes, can reach 7 10^{16} m^{-3} in APGD and RF-α modes and up to 4 10^{17} m^{-3} in a combination of APGD and RF-α modes (Hybrid). Time-resolved He(2^3S) densities show an overshoot on the ignition phase, which in RF-α mode can be attributed to a secondary source of ionization involving metastable atoms.

16:30

NW3 7 100% N_2 atmospheric-pressure microwave-line-plasma production with a modified waveguide structure* HARUKA SUZUKI, YUTO TAMURA, *Nagoya Univ.* HITOSHI ITOH, *Nagoya Univ., Tokyo Electron Ltd.* MAKOTO SEKINE, MASARU HORI, HIROTAKA TOYODA, *Nagoya Univ.* Large-scale atmospheric pressure (AP) plasmas have been given much attention because of its high cost benefit and a variety of possibilities for industrial applications. Microwave discharge plasma using slot antenna is attractive due to its ability of high-density and stable plasma production, and we have developed a long-scale AP microwave plasma (AP microwave line plasma: AP-MLP) source using loop-structured waveguide and travelling wave and have reported spatially-uniform AP-MLP of 40 cm in length using Ar or He gas discharge. However, rare gas discharge is not always suitable for industrial applications because usage of large volume rare gas degrades the AP cost benefit. Furthermore, many industrial applications require chemically-reactive species and the AP-MLP using molecular gas will drastically increase the applications of the AP-MLP. In this study, we demonstrate 100% N_2 discharge of the AP-MLP with a modified waveguide structure. Cross-sectional structure of the waveguide is improved to enhance the microwave electric field in the slot. 100% N_2 plasma of 15 cm-long is successfully produced using CW microwave power of 2 kW. Low gas temperature of 1000 K is confirmed by optical emission spectroscopy, suggesting applications of the AP-MLP to low temperature processes.

*Part of this work is supported by JSPS KAKENHI Grant Number 25286079.

16:45

NW3 8 Simplified modeling of pulsed corona for dielectric design of high-voltage devices SERGEY PANCHESHNYI, THOMAS SCHEFER, *ABB Corporate Research, Switzerland* Physics-based modeling of discharges in insulating gases (air, SF6, CO_2, etc.) is required for quantitative prediction of withstand voltages of high-voltage devices. Breakdown of not very long gaps at elevated pressures occurs typically by streamer (or spark) mechanism. Glow or streamer corona can delay the inception of breakdown streamers. This is often attributed to the so-called corona stabilization effect that is lowering of electric field close to the stressed electrodes due to corona space charge. However, compared to corona-less streamer breakdown of short gaps at elevated pressures, breakdown voltages are typically lower if corona starts. Direct simulation of discharges are often computationally costly, especially for 3D cases, and simplified engineering approaches are developing. Such models are then used for prediction of the "worst-case scenario", which might lead to breakdown of gaseous insulation in real design. The engineering models used for simulation of corona inception and development for different voltage shapes (DC, AC, pulsed) will be discussed for several geometries, including rod-plane case and electrode-less inception near a dielectric surface.

SESSION NW4: BASIC PLASMA PHYSICS I
Wednesday Afternoon, 12 October 2016
Room: 3 at 15:00
Peter Brinkmann, Ruhr University, presiding

Contributed Papers

15:00

NW4 1 Measurement of a comprehensive plasma parameter set in low pressure H_2 discharges for extended benchmarking of CR models STEFAN BRIEFI, *AG Experimentelle Plasmaphysik, Universitaet Augsburg, 86135 Augsburg* URSEL FANTZ, *Max-Planck-Institut fuer Plasmaphysik, Boltzmannstraße 2, 85748 Garching* In low pressure hydrogen discharges a variety of particles is present: besides electrons, the neutral species H_2 and H, the molecular ions H_2^+ and H_3^+ as well as protons and H^-. For a detailed assessment of the individual reactions occurring in those discharges, knowledge about the particular particle densities and temperatures is inevitable. An extensive determination of these plasma parameters has been carried out in a planar ICP in order to conduct an extended benchmark of collisional radiative models for atomic and molecular hydrogen as well as a benchmark of a dissociation model. As diagnostic methods energy resolved ion mass spectrometry has been applied for determining the ion densities and absolutely calibrated optical and VUV emission spectroscopy for measuring atomic and molecular emissivities as well as the density ratio of atomic to molecular hydrogen. A spatially movable Langmuir probe has been used for measuring the profiles of the electron temperature, density and the EEDF. Results are going to be presented for a variation of RF power and pressure.

15:15

NW4 2 Non-invasive determination of kinetic ion quantities and plasma parameters throughout the plasma sheath and bulk TSANKO VASKOV TSANKOV, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44780 Bochum, Germany* Ion velocity distribution functions (IVDF) are routinely measured to obtain information about the ions interacting with the surface. Here, we show that in charge-exchange (CX) collision dominated plasmas the distribution of the ions at the walls contains also information about the spatial distribution of the plasma parameters. This information can be extracted with the help of an exact solution of the Boltzmann equation including CX and ionization. Using the translation property of the solution the IVDF at any point in the plasma is reconstructed from the one measured at the wall. These spatially resolved distributions give the ionic parameters (density, mean velocity, energy and temperature) as exact kinetic averages. Further, the electric field, the plasma potential, and the electron density and temperature are also obtained from the IVDF. Good agreement with probe measurements is found. The method is most sensitive in the sheath and the near sheath region where the charge separation can be readily obtained. Results from an inductively-coupled plasma in neon are shown.

15:30

NW4 3 The correct kinetic Bohm criterion UWE CZARNETZKI, TSANKO VASKOV TSANKOV, *Institute for Plasma and Atomic Physics, Ruhr University Bochum, 44780 Bochum, Germany* Space charge sheaths are characteristic for bounded plasmas and are a key element in plasma-surface interactions. Hence, one of the most fundamental concepts in plasma physics – the Bohm criterion – is related to the definition of a sheath edge. However, its kinetic formulation is stirring controversies for a long time – from questioning its validity at high collisionality to claiming a divergence in its formulation. Here, based on a solution of the Boltzmann equation for ions with charge-exchange collisions and ionization both of these disputes are resolved: 1) The obtained form of the kinetic Bohm criterion removes the divergence in the ionic part. 2) It also introduces a new equally important term that describes collisional and geometric effects. This new term reestablishes the validity of the criterion at high collisionality. 3) It also restores agreement with the fluid counterpart of the criterion. The developed theory is supported by non-invasive spatially resolved measurements and a numerical model.

15:45

NW4 4 Reconsideration of basic concepts for the low-pressure discharge maintenance ANTONIA SHIVAROVA, *Sofia University* The Schottky condition and the concept for the ambipolar field known as bases of the low-pressure discharge maintenance are reconsidered. Whereas the Schottky condition results in a value of the electron temperature independent of the plasma density, the discussed generalized form of the Schottky condition relates – due to the nonlinear processes in the charged particle balance – the electron temperature to the plasma density, thus, ensuring self-consistency of the plasma description. The concept for equality of the electron and ion fluxes resulting into the ambipolar field is the second issue discussed. Localization of the power input outside the high plasma-density region, a common case in many rf plasma sources, breaks it down by transforming the ambipolar field into a vortex, non-conservative, field. Since the dc field in the discharge should be a potential (conservative) field, it appears to be composed by two vortex field: the ambipolar field and a field related to a vortex dc current, the latter driven by a deviation from the Boltzmann distribution of the electron density. In addition, due to the steady-state magnetic field self-induced by the vortex current in the discharge, the plasma appears magnetized without having an external magnetic field applied.

16:00

NW4 5 Non-locality, adiabaticity, thermodynamics and electron energy probability functions RODERICK BOSWELL, YUNCHAO ZHANG, CHRISTINE CHARLES, *Australian Natl Univ* KAZUNORI TAKAHASHI, *Tohoku University* Thermodynamic properties are revisited for electrons that are governed by nonlocal electron energy probability functions in a plasma of low collisionality. Measurements in a laboratory helicon double layer experiment have shown that the effective electron temperature and density show a polytropic correlation with an index of $\gamma_e = 1.17 \pm 0.02$ along the divergent magnetic field, implying a nearly isothermal plasma ($\gamma_e = 1$) with heat being brought into the system. However, the evolution of electrons along the divergent magnetic field is essentially an adiabatic process, which should have a $\gamma_e = 5/3$. The reason for this apparent contradiction is that the nearly collisionless plasma is very far from local thermodynamic equilibrium and the electrons behave nonlocally. The corresponding effective electron enthalpy has a conservation relation with the potential energy, which verifies that there is no heat transferred into the system during the electron evolution. The electrons are shown in nonlocal momentum equilibrium under the electric field and the gradient of the effective electron pressure. The convective momentum of ions, which can be assumed as a cold species, is determined by the effective electron pressure and the effective electron enthalpy is shown to be the source for ion acceleration. For these nearly collisionless plasmas, the use of traditional thermodynamic concepts can lead to very erroneous conclusions regarding the thermal conductivity.

16:15

NW4 6 Effect of collisions on the two-stream instability in a finite length plasma PETER L.G. VENTZEK, *Tokyo Electron America, Austin, Texas 78741, USA* DMYTRO SYDORENKO, *University of Alberta, Edmonton, Alberta T6G 2E1, Canada* IGOR D. KAGANOVICH, *Princeton Plasma Physics Laboratory* The instability of a monoenergetic electron beam in a collisional one-dimensional plasma bounded between grounded walls is considered both analytically and numerically. Collisions between electrons and neutrals are accounted for the plasma electrons only. Solution of a dispersion equation shows that the temporal growth rate of the instability is a decreasing linear function of the collision frequency which becomes zero when the collision frequency is two times the collisionless growth rate. This result is confirmed by fluid simulations. Practical formulas are given for the estimate of the threshold beam current which is required for the two-stream instability to develop for a given system length, neutral gas pressure, plasma density, and beam energy. Particle-in-cell simulations carried out with different neutral densities and beam currents demonstrate good agreement with the fluid theory predictions for both the growth rate and the threshold beam current.

16:30

NW4 7 Modeling of High-voltage Breakdown in Helium LIANG XU, *University of Science and Technology of China* ALEXANDER KHRABROV, IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA* TIMOTHY SOMMERER, *General Electric Research, Niskayuna, New York, USA* We investigate the breakdown in extremely high reduced electric fields (E/N) between parallel-plate electrodes in helium. The left branch of the Paschen curve in the voltage range of 20-350kV and inter-electrode gap range of 0.5-3.5cm is studied analytically and with Monte-Carlo/PIC simulations. The model incorporates electron, ion, and fast neutral species whose energy-dependent anisotropic scattering, as well as backscattering at the electrodes, is carefully taken into account. Our model demonstrates that (1) anisotropic scattering is indispensable for producing reliable results at such high voltage and (2) due to the heavy species backscattered at cathode, breakdown can occur even without electron- and ion-induced ionization of the background gas. Fast atoms dominate in the breakdown process more and more as the applied voltage is increased, due to their increasing ionization cross-section and to the copious flux of energetic fast atoms generated in charge-exchange collisions.

SESSION QR1: HEAVY PARTICLE COLLISIONS
Thursday Morning, 13 October 2016; Room: 1 at 8:30; Dmitry Fursa, Curtin University, presiding

Invited Papers

8:30

QR1 1 State-to-state measurements of low-energy ion-molecule and ion-ion collisions by three dimensional momentum imaging*
XAVIER URBAIN, *Université Catholique de Louvain*

While the measurement of total absolute cross sections remains challenging, the insight provided by differential cross sections and branching ratios is invaluable to assess the quality of theoretical predictions. Satisfactory agreement at the latter level gives better confidence in the proper identification of the reaction mechanism and key parameters. The three dimensional imaging of molecular dissociation, and more generally, the determination of all momentum vectors of the reaction products, gives direct access to the differential quantities of interest. For the prototype reaction of a proton colliding with H_2, the secondary H_2^+ current may be recorded to provide the total charge transfer yield. The dissociative charge transfer of the product ions with alkali targets leaves a characteristic signature in the total kinetic energy imparted to the H fragments. Its measurement is readily achieved by coincident detection on position sensitive detectors [1]. This allows us to extract vibrational populations as a function of collision energy. A resonant enhancement of the charge transfer around 45 eV/amu is observed, that leaves the molecular ion in its vibrational ground state [2]. Those observations are supported by state-of-the-art calculations. We have similarly explored the ionization of molecular oxygen by proton and alpha particle impact, at velocities characteristic of the solar wind. A somewhat more involved vibrational analysis of the O_2^+ cations [3] indicates a Franck-Condon like vibrational population of the ground electronic state from 50 eV to 10 keV, unlikely to modify the branching ratios of dissociative recombination, itself responsible for airglow emissions. More interestingly, a significant population of the $^4\Pi_u$ excited state is measured at velocities typical of the fast solar wind. Finally, we shall address the implementation of three dimensional imaging in merged ion-ion beam studies. Mutual neutralization involving anions and cations is a very efficient process, characterized by a uniquely defined initial state and a limited range of final states readily identified by the total kinetic energy released to the products. Detailed branching ratios may be obtained at near zero collision energy where the reaction rate is maximum and the system behaves as a quasi-molecule undergoing in flight dissociation. As an example, we shall discuss the mutual neutralization of C^+ and various anions of the second and third row of the periodic table [4].

*This work was supported by the Fonds de la Recherche Scientifique - FNRS through IISN Contract No. 4.4504.10.

[1]X. Urbain *et al.*, Rev. Sci. Instrum. **86**, 023305 (2015).
[2]X. Urbain *et al.*, Phys. Rev. Lett. **111**, 203201 (2013).
[3]A. Dochain and X. Urbain, EPJ Web Conf. **84**, 05001 (2015).
[4]R. F. Nascimento *et al.*, J. Phys. Conf. Ser. **635**, 022043 (2015).

Contributed Papers

9:00

QR1 2 Two-Centre Convergent Close-Coupling Approach to Ion-Atom Collisions: Current Progress* ALISHER KADYROV, ILKHOM ABDURAKHMANOV, JACKSON BAILEY, IGOR BRAY, *Curtin Univ of Technology* There are two versions of the convergent close-coupling (CCC) approach to ion-atom collisions: quantum-mechanical (QM-CCC) and semi-classical (SC-CCC). Recently, both implementations have been extended to include electron-transfer channels. The SC-CCC approach has been applied to study the excitation and the electron-capture processes in proton-hydrogen collisions. The integral alignment parameter A_{20} for polarization of Lyman-α emission and the cross sections for excitation and electron-capture into the lowest excited states have been calculated for a wide range of the proton impact energies. It has been established that for convergence of the results a very wide range of impact parameters (typically, 0-50 a.u.) is required due to extremely long tails of transition probabilities for transitions into the $2p$ states at high energies. The QM-CCC approach allowed to obtain an accurate solution of proton-hydrogen scattering problem including all underlying processes, namely, direct scattering and ionisation, and electron capture into bound and continuum states of the projectile. In this presentation we give a general overview of current progress in applications of the two-centre CCC approach to ion-atom and atom-atom collisions.

*The work is supported by the Australian Research Council.

9:15

QR1 3 Experimental and theoretical fully differential study of coherence effects in ionization of He by proton impact* MICHAEL SCHULZ, THUSITHA ARTHANAYAKA, BASU LAMICHHANE, *Missouri Univ of Sci & Tech* AHMAD HASAN, *UAE University* SUDIP GURUNG, JUAN REMOLINA, *Missouri Univ of Sci & Tech* SANDOR BORBELY, FERENC JARAI-SZABO, LADISLAU NAGY, *Babes-Bolyai University* We have measured and calculated fully differential cross sections (FDCS) for ionization of He by 75 keV proton impact. Results were obtained for transverse projectile coherence lengths of 3.3 and 1.0 a.u. The coherence length is related to the maximum dimension of a diffracting object that can be coherently illuminated by the projectiles. In the calculation impact parameter dependent amplitudes a(b) are computed and multiplied by a wave packet of varying width, reflecting the coherence length, which describes the projectile. The scattering angle dependent transition amplitude is then obtained from a Fourier transform. Pronounced coherence effects observed in the data are qualitatively well reproduced by the calculation. Along with extensive data published already the present work therefore confirms the presence of such effects beyond reasonable doubt.

*Work supported by NSF Grant No. PHY-1401586.

Invited Papers

9:30

QR1 4 Numerical calculation of charge exchange cross sections for plasma diagnostics*

LUIS MENDEZ, *Departamento de Quimica, Universidad Autonoma de Madrid*

The diagnostics of impurity density and temperature in the plasma core in tokamak plasmas is carried out by applying the charge exchange recombination spectroscopy (CXRS) technique [1], where a fast beam of H atoms collides with the plasma particles leading to electron capture reactions with the impurity ions. The diagnostics is based on the emission of the excited ions formed in the electron capture. The application of the CXRS requires the knowledge of accurate state-selective cross sections, which in general are not accessible experimentally, and the calculation of cross sections for the high n capture levels, required for the diagnostics in the intermediate energy domain of the probe beam, is particularly difficult. In this work, we present a lattice numerical method to solve the time dependent Schrödinger equation. The method is based on the GridTDSE package [2], it is applicable in the wide energy range 1 - 500 keV/u and can be used to assess the accuracy of previous calculations. The application of the method will be illustrated with calculations for collisions of multiply charged ions with H.

*Work partially supported by project ENE2014-52432-R (Secretaria de Estado de I+D+i, Spain).

[1]R. C. Isler, Plasma Phys. Control. Fusion **36**, 171 (1994).
[2]J. Suarez *et al.*, Comput. Phys. Commun. **180**, 2025 (2009).

Contributed Papers

10:00

QR1 5 Search for an explanation for neutralization rates of atomic ion-ion reactions* THOMAS M. MILLER, JUSTIN P. WIENS, NICHOLAS S. SHUMAN, ALBERT A. VIGGIANO, *Air Force Research Laboratory* We have measured well over a hundred rate coefficients k for cation-anion mutual neutralization reactions at thermal energies. For molecular ions, the k at 300 K tend not to vary more than a factor of two or three, presumably because a great many neutral states cross the incoming Coulombic potential energy curve. Atomic-atomic systems, for which there are few favorable curve crossings between the neutral and Coulombic curves, show variation of at least a factor of 60 in the measured k values at 300 K. For reactions involving the noble-gas cations, we assume that the final state is the lowest excited state of the neutral, plus the ground state of the neutralized anion, because otherwise the crossing distance R is so small that the curve-crossing probability is nil. We plotted measured k values (in cm^3/s) vs the distance R (in bohr) at which the neutral and Coulombic curves cross, the found that the data are fairly well fit by a power law for k, $10^{-4}R^{-2.8}$. The question is, is there a physical explanation for the observed dependence on R? We will discuss the data and the expectations of Landau-Zener theory.

*Supported by Air Force Office of Scientific Research (AFOSR-2303EP).

10:15

QR1 6 Effects of Angular Scattering on Ion Velocity Distribution Functions HUIHUI WANG, *University of Electronic Science and Technology of China* VLADIMIR SUKHOMLINOV, *St. Petersburg State University* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory* ALEXANDER MUSTAFAEV, *National Mineral-Resource University* An approximation model for total elastic and charge exchange ion-atom angular differential scattering cross sections is developed for simulations of the ion velocity distribution functions (IVDF) [1], which is validated by the experiment data of mobility and diffusion. IVDFs are simulated using the developed model and compared with recently published experimental data [2-3]. The IVDFs obtained with this model are compared to that from two other conventional models of less accurate differential cross sections [4-5]. The simulation results show the necessity to take into account the accurate differential cross sections, especially for strong E/N. The study reveals that IVDF cannot be separated into product of two independent IVDFs in the transverse and parallel to the electric field directions due to the significant effect of scattering.

[1]H. Wang *et al.*, Two Papers Submitted to Plasma Sources Sci. Technol. (2016).
[2]A. S. Mustafaev *et al.*, Technical Physics **60**, 1778 (2015).
[3]V. Sukhomlinov *et al.*, *42nd EPS Conference on Plasma Physics*, P5.168 (2015).
[4]A. V. Phelps, J. Appl. Phys. **76**, 747 (1994).
[5]M. Lampe *et al.*, Phys. Plasmas **19**, 113703 (2012).

SESSION QR2: PLASMA SURFACE INTERACTION

Thursday Morning, 13 October 2016; Room: 2a at 8:30; Peter Ventzek, Tokyo Electron, presiding

Invited Papers

8:30

QR2 1 Hybrid molecular dynamics simulation for plasma induced damage analysis

MASAAKI MATSUKUMA, *Tokyo Electron Limited*

In order to enable further device size reduction (also known as Moore's law) and improved power performance, the semiconductor industry is introducing new materials and device structures into the semiconductor fabrication process. Materials now include III-V compounds, germanium, cobalt, ruthenium, hafnium, and others. The device structure in both memory and logic has been evolving from planar to three dimensional (3D). One such device is the FinFET, where the transistor gate is a vertical fin made either of silicon, silicon-germanium or germanium. These changes have brought renewed interests in the structural damages caused by energetic ion bombardment of the fin sidewalls which are exposed to the ion flux from the plasma during the fin-strip off step. Better control of the physical damage of the 3D devices requires a better understanding of the damage formation mechanisms on such new materials and structures. In this study, the damage formation processes by ion bombardment have been simulated for Si and Ge substrate by Quantum Mechanics/Molecular Mechanics (QM/MM) hybrid simulations and compared to the results from the classical molecular dynamics (MD) simulations. In our QM/MM simulations, the highly reactive region in which the structural damage is created is simulated with the Density Functional based Tight Binding (DFTB) method and the region remote from the primary region is simulated using classical MD with the Stillinger-Weber and Moliere potentials. The learn on the fly method is also used to reduce the computational load. Hence our QM/MM simulation is much faster than the full QC-MD simulations and the original QM/MM simulations. The amorphous layers profile simulated with QM/MM have obvious differences in their thickness for silicon and germanium substrate. The profile of damaged structure in the germanium substrate is characterized by a deeper tail then in silicon. These traits are also observed in the results from the mass selected ion beam experiments. This observed damage profile dependence on species and substrate cannot be reproduced using classical MD simulations. While the Moliere potential is convenient to describe the interactions between halogens and other atoms, more accurate interatomic modeling such as DFTB method which takes the molecular orbitals into account should be utilized to make the simulations more realistic. Based on the simulations results, the damage formation scenario will be discussed.

Contributed Papers

9:00

QR2 2 Plasma Simulation in the Multiphysics Object Oriented Simulation Environment MOOSE STEVEN SHANNON, *North Carolina State Univ* ALEX LINDSAY, *University of Illinois* DAVID GRAVES, *University of California - Berkeley* CASEY ICENHOUR, DAVID PETERSON, *North Carolina State Univ* SCOTT WHITE, *MKS Instruments RF Power Division* MOOSE is an open source multiphysics solver developed by Idaho National Laboratory that is primarily used for the simulation of fission reactor systems; the framework is also well suited for the simulation of plasma systems given the development of appropriate modules not currently developed in the framework such as electromagnetic solvers, Boltzmann solvers, etc. It is structured for user development of application specific modules and is intended for both workstation level and high performance massively parallel environments. We have begun the development of plasma modules in the MOOSE environment and carried out preliminary simulation of the plasma/liquid interface to elucidate coupling mechanisms between these states using a fully coupled multiphysics model; these results agree well with PIC simulation of the same system and show strong response of plasma parameters with respect to electron reflection at the liquid surface. These results will be presented along with an overview of MOOSE and ongoing module development to extend capabilities to a broader set of research challenges in low temperature plasmas, with particular focus on RF and pulsed RF driven systems.

9:15

QR2 3 Electron Emission from Nano and MicroStructured Materials for Plasma Applications* MARLENE PATINO, *University of California, Los Angeles* YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* RICHARD WIRZ, *University of California, Los Angeles* Secondary electron emission (SEE) from plasma-confining walls can lead to adverse effects (e.g. increased plasma heat flux to the wall) in plasma devices, including plasma processing, confinement fusion, and plasma thrusters. Reduction in SEE from engineered materials with nm to mm-sized structures (grooves, pores, fibers), has been previously observed for primary electrons incident normal to the material. Here we present SEE measurements from one such engineered material, carbon velvet with microfibers (5 μm diameter, 1-2 mm length), and from a plasma-structured material, tungsten fuzz with nm fibers (35-50 nm diameter, 100-200 nm length). Additionally, dependence of SEE on incident angle was explored for tungsten fuzz. Results for carbon velvet and tungsten fuzz at normal incidence show 75% and 50% decrease in total yield from smooth graphite and tungsten, respectively. More notable is the independence of SEE on the incident angle for tungsten fuzz, as opposed to inverse cosine dependence for smooth materials. Hence, the reduction in SEE from tungsten fuzz is more pronounced at grazing angles. This is important for plasma-facing materials where a retarding plasma sheath leads to increased likelihood of plasma electrons impacting at grazing angles.

*This work was supported by DOE contract DE-AC02-09CH11466; AFOSR grants FA9550-14-1-0053, FA9550-11-1-0282, AF9550-

09-1-0695, and FA9550-14-10317; and DOE Office of Science Graduate Student Research Program.

9:30

QR2 4 Effects of Gas and Surface Temperatures during Cryogenic Etching of silicon with SF_6/O_2 STEFAN TINCK, ERIK NEYTS, *University of Antwerp* THOMAS TILLOCHER, REMI DUSSART, *Universite d'Orleans* ANNEMIE BOGAERTS, *University of Antwerp* PLASMANT TEAM, GREMI TEAM Cryogenic deep reactive ion etching (DRIE) of silicon and SiO_2 used for creating vias is investigated. The wafer is cooled to about −100 °C and a SF_6/O_2 mixture is applied. During cryogenic DRIE, a SiF_xO_y passivation layer is formed which prevents isotropic etching and the diffusion of F atoms into the Si or SiO_2 material. When the wafer is brought back to room temperature, this passivation layer desorbs naturally, leaving a clean trench with no scalloping. The primary issue with cryogenic DRIE is the high sensitivity to oxygen content and substrate or gas temperature. Both effects are investigated here. We believe that understanding the temperature dependent surface behavior of the O and F atoms to etch silicon is a primary step in obtaining full insight in the mechanisms of the SiFxOy passivation layer formation and automatic desorption. For this purpose, we apply a self-consistent model that covers both the bulk plasma characteristics as well as the surface processes during etching. Molecular Dynamics (MD) simulations are also performed to obtain insight in the surface reaction mechanisms. For validation of the modeling results, the etch rates are also experimentally obtained with reflectometry and Scanning Electron Microscopy (SEM) pictures.

9:45

QR2 5 Spectral Emission of fast non-Maxwellian Atoms at metallic Surfaces in low density Plasmas SVEN DICKHEUER, OLEKSANDR MARCHUK, *Forschungszentrum Juelich GmbH, IEK-4 Plasmaphysik, Trilateral Euregio Cluster (TEC), 52425 Juelich* CHRISTIAN BRANDT, *Max-Planck-Institut fuer Plasmaphysik, 17491 Greifswald, Germany* ALBRECHT POSPIESZCZYK, *Forschungszentrum Juelich GmbH, IEK-4 Plasmaphysik, Trilateral Euregio Cluster (TEC), 52425 Juelich* We have observed Doppler shifted components of the Balmer-lines emitted by fast non-Maxwellian atoms using different targets in a linear magnetized plasma in the PSI-2 device. In a pure hydrogen plasma the Doppler shifted components of the Balmer emission lines cannot be detected above the signal-to-noise-ratio [1]. However, in a mixed H/Ar plasma with composition of 1:1 the Doppler red- and blue-shifted components can be clearly observed. The Balmer-lines are analyzed by optical emission spectroscopy at observations angles of 35° and 90°. For target materials we use Ag, Pd, Fe and C. An acceleration potential can be applied to the target to change the kinetic energy of the incoming ions between 40 and 200 eV enabling the observation of the Doppler shifted components. The emission mechanism is discussed in details and is probably due to excitation transfer from metastable argon atoms to the fast hydrogen atoms. The Doppler shifted signal can be used to determine the properties of the surfaces, e.g., the energy and angular distribution of reflected atoms. Also the spectral reflectance of the target surface can be obtained and tested against the reference data and measurements with light calibration sources.

[1]C. Brandt *et al.*, EPS Conf. **O3**, J107 (2015).

Invited Papers

10:00

QR2 6 Atomic Precision Plasma Processing – Modeling Investigations

SHAHID RAUF, *Applied Materials, Inc., Santa Clara, California, USA*

Sub-nanometer precision is increasingly being required of many critical plasma processes in the semiconductor industry. Some of these critical processes include atomic layer etch and plasma enhanced atomic layer deposition. Accurate control over ion energy and ion / radical composition is needed during plasma processing to meet the demanding atomic-precision requirements. While improvements in mainstream inductively and capacitively coupled plasmas can help achieve some of these goals, newer plasma technologies can expand the breadth of problems addressable by plasma processing. Computational modeling is used to examine issues relevant to atomic precision plasma processing in this paper. First, a molecular dynamics model is used to investigate atomic layer etch of Si and SiO_2 in Cl_2 and fluorocarbon plasmas. Both planar surfaces and nanoscale structures are considered. It is shown that accurate control of ion energy in the sub-50 eV range is necessary for atomic scale precision. In particular, if the ion energy is greater than 10 eV during plasma processing, several atomic layers get damaged near the surface. Low electron temperature (T_e) plasmas are particularly attractive for atomic precision plasma processing due to their low plasma potential. One of the most attractive options in this regard is energetic-electron beam generated plasma, where T_e <0.5 eV has been achieved in plasmas of molecular gases. These low T_e plasmas are computationally examined in this paper using a hybrid fluid-kinetic model. It is shown that such plasmas not only allow for sub-5 eV ion energies, but also enable wider range of ion / radical composition. Coauthors: Jun-Chieh Wang, Jason Kenney, Ankur Agarwal, Leonid Dorf, and Ken Collins.

SESSION QR3: STREAMER AND BREAKDOWN PROCESSES

Thursday Morning, 13 October 2016; Room: 2b at 8:30; Natalia Babaeva, Joint Institute for High Temperatures RAS, presiding

Invited Papers

8:30

QR3 1 Fluid and hybrid models for streamers*

ZDENĚK BONAVENTURA, *Department of Physical Electronics, Fac. Sci., Masaryk University, Brno, Czech Republic*

Streamers are contracted ionizing waves with self-generated field enhancement that propagate into a low-ionized medium exposed to high electric field leaving filamentary trails of plasma behind. The widely used model to study streamer dynamics is based on drift-diffusion equations for electrons and ions, assuming local field approximation, coupled with Poisson's equation. For problems where presence of energetic electrons become important a fluid approach needs to be extended by a particle model, accompanied also with Monte Carlo Collision technique, that takes care of motion of these electrons. A combined fluid-particle approach is used to study an influence of surface emission processes on a fast-pulsed dielectric barrier discharge in air at atmospheric pressure. It is found that fluid-only model predicts substantially faster reignition dynamics compared to coupled fluid–particle model. Furthermore, a hybrid model can be created in which the population of electrons is divided in the energy space into two distinct groups: (1) low energy 'bulk' electrons that are treated with fluid model, and (2) high energy 'beam' electrons, followed as particles. The hybrid model is then capable not only to deal with streamer discharges in laboratory conditions, but also allows us to study electron acceleration in streamer zone of lighting leaders. There, the production of fast electrons from streamers is investigated, since these (runaway) electrons act as seeds for the relativistic runaway electron avalanche (RREA) mechanism, important for high-energy atmospheric physics phenomena. Results suggest that high energy electrons effect the streamer propagation, namely the velocity, the peak electric field, and thus also the production rate of runaway electrons.

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

Contributed Papers

9:00

QR3 2 Magnetic field effects on the propagation of positive streamers ANBANG SUN, *State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi'an Jiaotong University, Xi'an 710049, China* JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica (CWI), Amsterdam, The Netherlands* UTE EBERT, *Centrum Wiskunde & Informatica (CWI), The Netherlands; Department of Applied Physics, Eindhoven University of Technology, The Netherlands* We investigate how strong magnetic fields affect the propagation of positive streamer discharges. Because such discharges grow opposite to the electron drift direction, they require a source of electrons ahead of them. Here we focus on air, in which photoionization supplies such free electrons isotropically around the streamer head. Using a 3D particle model, we investigate how strong transverse magnetic fields alter the trajectory, ionization rate and energy of these source electrons, leading to streamer branching in the plane spanned by E and B.

9:15

QR3 3 Two-Dimensional Electron Density Measurement of Positive Streamer Discharge in Atmospheric-Pressure Air* YUKI INADA, *Saitama University* RYO ONO, AKIKO KUMADA, KUNIHIKO HIDAKA, *The University of Tokyo* MITSUAKI MAEYAMA, *Saitama University* The electron density of streamer discharges propagating in atmospheric-pressure air is crucially important for systematic understanding of the production mechanisms of reactive species utilized in wide ranging applications such as medical treatment, plasma-assisted ignition and combustion, ozone production and environmental pollutant processing. However, electron density measurement during the propagation of the atmospheric-pressure streamers is extremely difficult by using the conventional localized type measurement systems due to the streamer initiation jitters and the irreproducibility in the discharge paths. In order to overcome the difficulties, single-shot two-dimensional electron density measurement was conducted by using a Shack-Hartmann type laser wavefront sensor. The Shack-Hartmann sensor with a temporal resolution of 2 ns was applied to pulsed positive streamer discharges generated in an air gap between pin-to-plate electrodes. The electron density a few ns after the streamer initiation was $7*10^{21}m^{-3}$ and uniformly distributed along the streamer channel. The electron density and its distribution profile were compared with a previous study simulating similar streamers, demonstrating good agreement.

*This work was supported in part by JKA and its promotion funds from KEIRIN RACE. The authors like to thank Mr. Kazuaki Ogura and Mr. Kaiho Aono of The University of Tokyo for their support during this work.

9:30

QR3 4 Mechanism of bullet-to-streamer transition in water surface incident helium atmospheric pressure plasma jet (APPJ)* SUNG-YOUNG YOON, *Natl Fusion Res Inst* GON-HO KIM, *Seoul National Univerity* SU-JEONG KIM, *Hanwha chemical coorperation* BYEONGJUN BAE, *Seoul National Univerity* SEONG BONG KIM, SEUNGMIN RYU, SUK JAE YOO, *Natl Fusion Res Inst* The mechanism of bullet to streamer transition of helium-APPJ bullet on the electrolyte surface was investigated. The APPJ was discharged in pin-to-ring DBD reactor system with helium gas by applying the ac-driven voltage at a frequency of 10 kHz. The water evaporation was controlled via saline temperature. The temporal- and 2-dimensional spatially- resolved plasma properties are monitored by optical diagnostics. During the APPJ bullet propagation from reactor to electrolyte surface, the transition of bullet from streamer was recognized from the high speed image, hydrogen beta emission line, and bullet propagation speed. The He metastable species density profiles from the tunable diode laser absorption spectroscopy (TDLAS) showed the metastable lost the energy near electrolyte surface. It is found that the bullet transited to streamer when the water fraction reached to ~29%. This can be fascinating result to study the plasma physics liquid surface, non-fixed boundary.

*Acknowledgements: This work was partly supported by R&D Program of 'Plasma Advanced Technology for Agriculture and Food (Plasma Farming)' through the National Fusion Research Institute of Korea (NFRI) funded by the Government fund was carried out as part.

9:45

QR3 5 Distinctive features of kinetics of plasma at high specific energy deposition NIKITA LEPIKHIN, *Ecole Polytechnique, France* NIKOLAY POPOV, *Skobeltsyn Institute of Nuclear Physics (MSU), Russia* SVETLANA STARIKOVSKAIA, *Ecole Polytechnique, France* A nanosecond capillary discharge in pure nitrogen at moderate pressures is used as an experimental tool for plasma kinetics studies at conditions of high specific deposited energy up to 1 eV/molecule. Experimental observations based on electrical (back current shunts, capacitive probe) and spectroscopic measurements (quenching rates; translational, rotational and vibrational temperature measurements) demonstrate that high specific deposited energy, at electric fields of 200-300 Td, can significantly change gas kinetics in the discharge and in the afterglow. The numerical calculations in 1D axially symmetric geometry using experimental data as input parameters show that changes in the plasma kinetics are caused by extremely high excitation degree: up to 10% of molecular nitrogen is electronically excited at present conditions. Distinctive features of kinetics of plasma at high specific energy deposition as well as details of the experimental technique and numerical calculations will be present. The work was partially supported by French National Agency, ANR (PLASMAFLAME Project, 2011 BS09 025 01), AOARD AFOSR, FA2386-13-1-4064 grant (Program Officer Prof. Chiping Li), LabEx Plas@Par and Linked International Laboratory LIA KaPPA (France-Russia).

10:00

QR3 6 Parameters of Runaway Electron Beams at a Subnanosecond Breakdown of Gases at Atmospheric Pressure* VICTOR TARASENKO, *Head of laboratory* INSTITUTE OF HIGH CURRENT ELECTRONICS COLLABORATION, NATIONAL RESEARCH TOMSK POLYTECHNIC UNIVERSITY COLLABORATION The generation of runaway electrons in gases at atmospheric pressure is a fundamental physical phenomenon. The aim of this work is to determine the main parameters of runaway electron beams at a subnanosecond breakdown of gases at atmospheric pressure from experiments performed with the highest currently achieved time resolution. Studies were performed with five experimental setups and three generators of nanosecond pulses with the duration of the voltage pulse front from 0.1 to 1 ns and the amplitude of the voltage pulse in the incident wave from 40 to 200 kV. It has been proven that the duration of the current pulse of the runaway electron beam detected behind the foil of the gas diode in air and other gases at atmospheric pressure was ~100 ps. It has been shown that the use of a collimator with a hole with a diameter of 1 mm or smaller, short interelectrode gaps, and cathodes with a small area of a sharp edge makes it possible to separate a fraction of runaway electrons of the beam and to detect pulses with a FWHM of about 25 ps. The number of electrons detected behind the anode foil was correspond to a current amplitude of the runaway electron beam of 100 A.

*This work was supported by the Russian Science Foundation under the Grant Number 14-29-00052.

10:15

QR3 7 Experimental study of plume induced by nanosecond repetitively pulsed spark microdischarges in air at atmospheric pressure THOMAS ORRIERE, NICOLAS BENARD, ERIC MOREAU, DAVID PAI, *Institut PPRIME (CNRS UPR 3346, Université de Poitiers, ISAE-ENSMA)* Nanosecond repetitively pulsed (NRP) spark discharges have been widely studied due to their high chemical reactivity, low gas temperature, and high ionization efficiency. They are useful in many research areas: nanomaterials synthesis, combustion, and aerodynamic flow control. In all of these fields, particular attention has been devoted to chemical species transport and/or hydrodynamic and thermal effects for applications. The aim of this study is to generate an electro-thermal plume by combining an NRP spark microdischarge in a pin-to-pin configuration with a third DC-biased electrode placed a few centimeters away. First, electrical characterization and optical emission spectroscopy were performed to reveal important plasma processes. Second, particle image velocimetry was combined with schlieren photography to investigate the main characteristics of the generated flow. Heating processes are measured by using the $N_2(C \rightarrow B)$ (0,2) and (1,3) vibrational bands, and effects due to the confinement of the discharge are described. Moreover, the presence of atomic ions N^+ and O^+ is discussed. Finally, the electro-thermal plume structure is characterized by a flow velocity around 1.8 $m.s^{-1}$, and the thermal kernel has a spheroidal shape.

SESSION QR4: BASIC PLASMA PHYSICS II

Thursday Morning, 13 October 2016; Room: 3 at 8:30; Tsanko Tsankov, Ruhr University, presiding

Invited Papers

8:30

QR4 1 Collective dynamics and transport in extremely magnetized dusty plasmas*

PETER HARTMANN, *Wigner Research Centre for Physics, Hungarian Academy of Sciences*

We have built an experimental setup to realize and observe rotating dusty plasmas in a co-rotating frame. Based on the Larmor theorem, the "RotoDust" setup is able to create effective magnetizations, mimicked by the Coriolis inertial force, in strongly coupled dusty plasmas that are impossible to approach with superconducting magnets. At the highest rotation speed, we have achieved effective magnetic fields of 3200 T [1]. The effective magnetization $\beta = \omega_c/\omega_p$ (ratio of cyclotron to plasma frequency) reaches 0.76 which is typical for many strongly magnetized and strongly correlated plasmas in compact astrophysical objects [2]. The analysis of the wave spectra as observed in the rotating frame clearly shows the equivalence of the rotating dust cloud and a magnetized plasma. Further, the analysis of the mean square displacement (MSD) and the velocity autocorrelation function (VAC) revealed the transport parameters diffusion and viscosity, which are in reasonable agreement with numerical predictions for magnetized 2D Yukawa systems. Small degree of super-diffusion is observed.

*This research was supported by grant NKFIH K-115805 and the Janos Bolyai Research Scholarship of the HAS.

[1]P. Hartmann, Z. Donkó, T. Ott, H. Kählert, and M. Bonitz, Phys. Rev. Lett. **111**, 155002 (2013).
[2]H. Kählert, J. Carstensen, M. Bonitz, H. Löwen, F. Greiner, and A. Piel, Phys. Rev. Lett. **109**, 155003 (2012).
[3]T. Ott and M. Bonitz, Phys. Rev. Lett. **107**, 135003 (2011).

Contributed Papers

9:00

QR4 2 Rotating plasma structures in the cross-field discharge of Hall thrusters STEPHANE MAZOUFFRE, LOU GRIMAUD, SEDINA TSIKATA, *CNRS - ICARE* KONSTANTIN MATYASH, *Ernst Moritz Arndt University* Rotating plasma structures, also termed rotating spokes, are observed in various types of low-pressure discharges with crossed electric and magnetic field configurations, such as Penning sources, magnetron discharges, negative ion sources and Hall thrusters. Such structures correspond to large-scale high-density plasma blocks that rotate in the E×B drift direction with a typical frequency on the order of a few kHz. Although such structures have been extensively studied in many communities, the mechanism at their origin and their role in electron transport across the magnetic field remain unknown. Here, we will present insights into the nature of spokes, gained from a combination of experiments and advanced particle-in-cell numerical simulations that aim at better understanding the physics and the impact of rotating plasma structures in the ExB discharge of the Hall thruster. As rotating spokes appear in the ionization region of such thrusters, and are therefore difficult to probe with diagnostics, experiments have been performed with a wall-less Hall thruster. In this configuration, the entire plasma discharge is pushed outside the dielectric cavity, through which the gas is injected, using the combination of specific magnetic field topology with appropriate anode geometry.

9:15

QR4 3 Hybrid Simulation of Supersonic Flow of Weakly Ionized Plasma along Open Field Magnetic Line Effect of Background Pressure AMPAN LAOSUNTHARA, HIROSHI AKATSUKA, *Tokyo institute of technology* In previous study, we experimentally examined physical properties of supersonic flow of weakly ionized expanding arc-jet plasma through an open magnetic field line (B_{max}~0.16T). We found supersonic velocity of helium plasma up to Mach ~3 and the space potential drop at the end of the magnets. To understand the plasma in numerical point of view, the flows of ion and neutral are treated by particle-based Direct Simulation Monte Carlo (DSMC) method, electron is treated as a fluid. The previous numerical study, we assumed 2 conditions. Ion and electron temperatures were the same (LTE condition). Ion and electron velocities were the same (current-free condition). We found that ion velocity decreased by collision with residual gas molecules (background pressure). We also found that space potential changing with background pressure. In other words, it was indicated that electric field exists and the current-free assumption is not proper. In this study, we add electron continuity and electron momentum equations to obtain electron velocity and space potential. We find that space potential changing with background pressure slightly. It is indicated that electron is essential to space potential formation than ion.

9:30

QR4 4 The helical kink "STABILITY" in plasmas MASARU IRIE, *Waseda University* MIYOKO KUBO-IRIE, *The Open University of Japan* The helical plasma "instability" was known for half a century before and it was one of the key issue in the plasma fusion research. The three dimensional MHD simulation on the low pressure linear plasma has been conducted in National Institute of Fusion Sciences around 80's in the consequence with plasma reconnection and Dynamo-effect closely related to the Reversed Field Pinch Plasma as well as the Spheromak / Compact Torus. Both of these trends aiming for controlling the plasma instability especially with current density over 1MA/m^2. On the other hand in arc discharge field, helical plasma instability in the current zero region was one of the main issue and explained especially in "this: Ruhr University Bochum" under Prof. Jurgen Mentel. In this proposed presentation, we would like to concentrate on controlling the plasma profile and demonstrate the existence of the "stable" helical plasma and discuss the application of these techniques by applying massively parallel but bench top GPGPU system. This should give good simulation on the fusion plasma such as the Internal Transport Barriers and Serpens mode.

[1]H. G. Hulsman and J. Mnetel, Phys. Fluids **30**, 2275 (1987).
[2]T. Sato, T. Hayashi, and R. Horiuchi, Private Communication.

9:45

QR4 5 Electron drift across the magnetic field in a micro-ECR neutralizer YOSHINORI TAKAO, KENTA HIRAMOTO, *Yokohama National University* YUICHI NAKAGAWA, HIROYUKI KOIZUMI, KIMIYA KOMURASAKI, *The University of Tokyo* Although neutralization is required for ion propulsion systems to produce thrust by ion beams in space, a neutralizer itself should be low-power and low-propellant consumption because electrons make no thrust. To design such a micro neutralizer, the mechanisms of electron transport should be elucidated. In the present study, three-dimensional particle-in-cell simulations have been conducted for a 4.2-GHz microwave discharge neutralizer, using an electron cyclotron resonance xenon plasma. The size of the discharge chamber is 20 × 20 × 4 mm^3 and a plate with four orifices is placed at the downstream of the chamber. The calculations were performed at the gas pressure of 1 mTorr and the absorbed power of 0.3 W. The simulation results have indicated that the electrostatic field inside the plasma source has a dominant effect on the electron extraction. When the electrons are trapped in the magnetic field passing close to the orifice, such electrons can be extracted from the plasma source to the outside at the orifice edge because of the **E** × **B** drift. The **E** × **B** drift also seems to play a significant role in electron transport from the ECR layer to the orifice plate across the magnetic field.

SESSION RR1: ELECTRICAL DIAGNOSTICS II
Thursday Morning, 13 October 2016; Room: 1 at 11:00; Alan Howling, Swiss Plasma Center, presiding

Invited Papers

11:00

RR1 1 Development and Miniaturization of RF based probes for Electron Density Measurements
KEIJI NAKAMURA, *Chubu University*

To make a diagnostics on plasmas for materials processing plasmas accompanying with deposition of non-conducting films in etching and/or CVD processes, curling probe (CP) with a spiral slot antenna has been recently developed as a compact diagnostic tool which enables the local electron density measurement. The electron density is obtained from a shift of the probe resonance frequency in discharge ON and OFF monitored by a network analyzer (NWA). A conventional CP has a diameter larger than ~15 mm typically, because a slot length of the CP is as long as several tens millimeters for its resonance frequency less than several GHz. Further miniaturization of the CP was required to expand applicable range to various plasma sources like a narrow-gap parallel plate discharge. We tried miniaturization of the CP down to less than ~3 mm in the probe diameter by fabricating narrow spiral slot antenna, and experimentally and numerically the miniaturized probe was investigated how much influence the slot width has on probe resonance characteristics and electron density measurements. In the case of the conventional CP made of stainless steel, ~0.3-mm-wide normal slot antenna, the resonance spectra was clearly observed regardless of antenna materials of copper or stainless steel (SS). However, when the slot width was reduced down to ~0.03 mm, the slot resonance was strongly dependent on the antenna materials. Namely the resonance peak was almost vanished for the SS antenna, whereas clearly appeared for the copper antenna. In general, the narrower the slot is, the higher attenuation factor the slot has for electromagnetic wave propagating along the slot. In such an attenuated transmission line of the narrow slot, high electric conductivity of the antenna seems preferable for the slot resonance. Furthermore, the miniaturized CP with the copper antenna was also introduced into low pressure (<~1Pa) Ar plasma. The resonance frequency was confirmed to changes sensitively with electron density, suggesting the miniaturized CP will be available to electron density measurements. Numerical simulation showed that localization of electromagnetic fields near the slot was remarkably enhanced by decreasing in the slot width, suggesting that the miniaturized CP suffers from more significant sheath effects compared to the conventional CP.

Contributed Papers

11:30

RR1 2 Simulation of reactive and resistive resonances of a curling probe for low and high pressure plasma diagnostics ALI ARSHADI, RALF PETER BRINKMANN, *Ruhr University Bochum* Curling probe (CP) as a novel realization of "Active Plasma Resonance Spectroscopy" concept, reveals a great ability for electron density measurement in a low pressure plasma. A weak RF signal is coupled into the plasma via a CP. The spectral response of the plasma is recorded and a mathematical model is used to determine the electron density. The CP is a spiral slot resonating at distinctive frequencies which are strongly dependent on the electron density. Since the CP can be miniaturized and flatly embedded into the chamber wall, the perturbation and metal contamination are negligible. With the assumption of little spiralization effect, this work investigates a "straightened" CP. The diffraction of an incident plane wave at a rectangular slot is calculated by solving Maxwell's equations and the cold plasma model simultaneously. In low pressure plasmas two kinds of reactive resonance are observed. The lower frequency of resonance has a surface wave characteristic and the higher one is associated with the wave propagation along the probe length. In high pressure plasmas reactive resonance is not observed but a resistive reonance even at frequencies smaller than the surface wave frequency is excited. Good agreement of our computations with the numerical results is shown.

11:45

RR1 3 Accuracy of cutoff probe for measuring electron density: simulation and experiment DAE-WOONG KIM, SHIN-JAE YOU,* SI-JUNE KIM, JANG-JAE LEE, *Physics, Chungnam national university* JUNG-HYUNG KIM, *Vacuum center, Korea research institute of standard and science* WANG-YUHL OH, *Mechanical engineering, Korea advanced institute of science and technology* The electron density has been used for characterizing the plasma for basic research as well as industrial application. To measure the exact electron density, various type of microwave probe has been developed and improved. The cutoff probe is a promising technique inferring the electron density from the plasma resonance peak on the transmission spectrum. In this study, we present the accuracy of electron density inferred from cutoff probe. The accuracy was investigated by electromagnetic simulation and experiment. The discrepancy between the electron densities from the cutoff probe and other sophisticated microwave probes were investigated and discussed. We found that the cutoff probe has good accuracy in inferred electron density.

*corresponding author.

12:00

RR1 4 Accompanying indicators of plasma potential when using impedance probes in low density plasma* DAVID WALKER, *Sotera Defense Solutions, Inc.* DAVID BLACKWELL, *Naval Research Laboratory* RICHARD FERNSLER, *Sotera Defense Solutions, Inc.* WILLIAM AMATUCCI, *Naval Research Laboratory* In earlier works, we used spheres of various sizes as impedance probes in demonstrating a method of determining plasma potential, φ_p, when the probe radius, r_p, is much larger than λ_D [1,2]. These works demonstrate a method of measuring plasma potential with an impedance probe by applying a small amplitude rf signal and tracking a minimum in $\mathrm{Re}(Z_{ac})$ as a function of probe bias, V_b where $\mathrm{Re}(Z_{ac})$ and $\mathrm{Im}(Z_{ac})$ are available using a network analyzer through measurement of the reflection coefficient, Γ. However, for borderline cases where the requirement that $r_p \gg \lambda_D$ begins to fail, $\mathrm{Re}\,(Z_{ac})$ ($\sim 1/n_e$) can rise to kΩ's for even moderate levels of V_b, causing a large impedance mismatch with the network analyzer ($Z_0 = 50\Omega$). The purpose of the recent work is to demonstrate that Γ itself along with $\mathrm{Im}(Z_{ac})$ and their derivatives are useful as accompanying indicators to $\mathrm{Re}(Z_{ac})$ in these difficult cases [3]. We will present experimental data along with model comparisons to demonstrate the usefulness and limits of the additional indicators.

*Work Supported by Naval Research Laboratory Base Program.

[1]Phys. Plasmas **17**, 113503 (2010).
[2]US Patent 8, 175, 827 B2 (5/2012).
[3]Phys. Plasmas **22**, 083505 (2015).

12:15

RR1 5 Diagnostics of plasma and particle flows extracted from bipolar gridded plasma sources STANISLAV DUDIN, *V N Karazin Kharkiv National University, Kharkiv UKRAINE* DMYTRO RAFALSKYI, *Laboratoire de Physique des Plasmas, Ecole Polytechnique, Palaiseau FRANCE* ANE AANESLAND, *CNRS, Laboratoire de Physique des Plasmas, Ecole Polytechnique, Palaiseau FRANCE* Gridded plasma sources have a strong interest from both industry and research community due to large number of their applications, including electric propulsion, plasma acceleration for fundamental studies, ion beam surface treatment and semiconductor etching, etc. Commonly, a dc electric field is applied between the grids of these sources to accelerate positive ions, while the space charge compensation of the beam is achieved using an additional external electron source. Few recent concepts assume bipolar extraction of particles, such that both positive and negative particles are extracted from plasma and accelerated. The formed beam can be composed of extracted continuously or alternately positive and negative ions, or positive ions and electrons. Diagnostics of these beams is a challenging task, in particular absolute flux and energy distribution measurements for different species present in the bipolar beam. In this work we present few recent diagnostic techniques allowing to measure absolute fluxes and energies of +/- ions and electrons, and also methods to investigate temporal behavior of these flows.

SESSION RR2: PLASMA DEPOSITION II
Thursday Morning, 13 October 2016
Room: 2a at 11:00
Doug Kell, Lam Research Corporation, presiding

Contributed Papers

11:00

RR2 1 Selective deposition for "chamber clean-free" processes using tailored voltage waveform plasmas JUNKANG WANG, ERIK V. JOHNSON, *LPICM, CNRS, École Polytechnique, Université Paris Saclay* Tailored Voltage Waveforms (TVWs) have been proven capable of creating plasma asymmetries in otherwise symmetric CCP reactors. Particularly, sawtooth TVWs (described as having strong slope-asymmetry due to different voltage rise/fall slope) can lead to different sheath dynamics, thus generating strongly asymmetric ionization near each electrode. To date, research concerning the slope-asymmetry has only focused on single-gas plasmas. Herein, we present a study looking at $SiF_4/H_2/Ar$ mixtures to investigate silicon thin film deposition. The resulting surface process depends strongly on multiple precursors, and the deposition requires a specific balance between surface arrival rates of SiF_x and H. For a certain gas flow ratio, we can obtain a deposition rate of 0.82Å/s on one electrode and an etching rate of 1.2Å/s on the other. Moreover, the deposition/etching balance can be controlled by H_2 flow and waveform amplitude. This is uniquely possible due to the mixed-gas nature of the process and localized ionization generated by sawtooth TVWs. This encourages the prospect that one could choose process conditions to achieve a variety of desired depositions on one electrode, while leaving the other pristine.

11:15

RR2 2 Thin film deposition using rarefied gas jet DR. SAHADEV PRADHAN, *Dept. of Chemical Engineering, Indian Institute of Science, Bangalore-560 012, India* The rarefied gas jet of aluminium is studied at Mach number $Ma = (Uj/\sqrt{kbT_j/m})$ in the range $.01 < Ma < 2$, and Knudsen number $Kn = (1/(\sqrt{2}\pi\, d^2 n_d H)$ in the range $.01 < Kn < 15$, using two-dimensional (2D) direct simulation Monte Carlo (DSMC) simulations, to understand the flow phenomena and deposition mechanisms in a physical vapor deposition (PVD) process for the development of the highly oriented pure metallic aluminum thin film with uniform thickness and strong adhesion on the surface of the substrate in the form of ionic plasma, so that the substrate can be protected from corrosion and oxidation and thereby enhance the lifetime and safety, and to introduce the desired surface properties for a given application. Here, H is the characteristic dimension, U_j and T_j are the jet velocity and temperature, n_d is the number density of the jet, m and d are the molecular mass and diameter, and kb is the Boltzmann constant. An important finding is that the capture width (cross-section of the gas jet deposited on the substrate) is symmetric around the centerline of the substrate, and decreases with increased Mach number due to an increase in the momentum of the gas molecules. DSMC simulation results reveals that at low Knudsen number ((Kn=0.01); shorter mean free paths), the atoms experience more collisions, which direct them toward the substrate. However, the atoms also move with lower momentum at low Mach number, which allows scattering collisions to rapidly direct the atoms to the substrate.

11:30

RR2 3 Effects of Various RF Powers on CdTe Thin Film Growth Using RF Magnetron Sputtering MOHAMMAD ALIBAKHSHI, ZOHREH GHORANNEVIS, *Department of Physics, Azad University, Tehran, Iran* Cadmium telluride (CdTe) film was deposited using the magnetron sputtering system onto a glass substrate at various deposition times and radio frequency (RF) powers. Ar gas was used to generate plasma to sputter the CdTe atoms from CdTe target. Effects of two experimental parameters of deposition time and RF power were investigated on the physical properties of the CdTe films. X-ray Diffraction (XRD) analysis showed that the films exhibited polycrystalline nature of CdTe structure with the (111) orientation as the most prominent peak. Optimum condition to grow the CdTe film was obtained and it was found that increasing the deposition time and RF power increases the crystallinity of the films. From the profilometer and XRD data's, the thicknesses and crystal sizes of the CdTe films increased at the higher RF power and the longer deposition time, which results in affecting the band gap as well. From atomic force microscopy (AFM) analysis we found that roughnesses of the films depend on the deposition time and is independent of the RF power.

11:45

RR2 4 Plasma Assisted Growth of MoNi Thin Films and Its Physical Characterization ZOHREH GHORANNEVIS, ELAHEH AKBARNEJAD, MAHMOOD GHORANNEVISS, *Department of Physics, Azad University, Iran* In this paper effects of a RF power and a deposition time on physical properties of Mo-Ni films were studied systematically. Deposition of Mo-Ni film is performed using RF magnetron sputtering system on soda lime glass. Argon gas is used to sputter the atoms of Mo and Ni from Mo-Ni target. Structural, morphological, optical and electrical properties of the films are studied using X-ray diffractometer (XRD), field emission scanning electron microscopy (FESEM), atomic force microscopy (AFM), spectrophotometer and four point probe, respectively. We found that by increasing the RF power, structure of the film can change from Mo to Mo-Ni, which is due to the higher sputtering yield of the Ni at higher RF powers. On the other hand, changing the deposition time also affected the physical properties of the Mo-Ni films. By increasing the deposition time crystalline structure significantly improved and the resistivity of the films decreased as a result of higher content of the Ni atoms amount.

12:00

RR2 5 Atmospheric inductively coupled Ar/H_2 plasma torch for spraying B_4C/Cu functionally gradient material PENG ZHAO, LIN LI, QIJIA GUO, GUOHUA NI, XIAODONG ZHANG, *Institute of Plasma Physics, Chinese Academy of Sciences, PO Box 1126, Hefei 230031, China* INSTITUTE OF PLASMA PHYSICS, CHINESE ACADEMY OF SCIENCES TEAM For preparing plasma facing material (PFM) in fusion device, an Ar/H_2 inductively coupled plasma torch driven by a 24-60 MHz RF power is developed for spraying B_4C/Cu functionally gradient material (FGM). In previous studies, we found that by adding a fractional amount of H_2 gas into Ar plasma, quality of B_4C/Cu coating was significantly improved. To discuss the effect of ingredient and the flow rate of plasma gas and frequency of the RF power on plasma characteristics, the optical emission spectroscopy (OES) measurement was performed. The gas rotational temperature is determined by simulating experimental hydroxyl spectra. The excitation temperature is estimated by the ratio of the intensities of the spectral lines of Ar I based on Boltzmann's method. The effects on B_4C/Cu coating quality were studied by means of X-ray photoelectron spectrometry (XPS), scanning electron microscope (SEM) and energy dispersive spectrometer (EDS). All the plasma properties and the results of B_4C/Cu coating would give us an insight on the mechanism and the possibility of improving the process.

12:15

RR2 6 Modelling the plasma plume of an assist source in PIAD* JOCHEN WAUER, JENS HARHAUSEN, RÜDIGER FOEST, DETLEF LOFFHAGEN, *Leibniz Institute for Plasma Science and Technology* Plasma ion assisted deposition (PIAD) is a technique commonly used to produce high-precision optical interference coatings. Knowledge regarding plasma properties is most often limited to dedicated scenarios without film deposition [1]. Approaches have been made to gather information on the process plasma in situ [2] to detect drifts which are suspected to cause limits in repeatability of resulting layer properties. Present efforts focus on radiance monitoring of the plasma plume of an Advanced Plasma Source (APSpro, Bühler) by optical emission spectroscopy to provide the basis for an advanced plasma control. In this contribution modelling results of the plume region are presented to interpret these experimental data. In the framework of the collisional radiative model used [3], 15 excited neutral argon states in the plasma are considered. Results of the species densities show good consistency with the measured optical emission of various argon $2p - 1s$ transitions.

*This work was funded by BMBF under grant 13N13213.

[1]Harhausen *et al.*, Plasma Sources Sci. Technol. **21**, 035012 (2012).
[2]Styrnoll *et al.*, Plasma Sources Sci. Technol. **22**, 045008 (2013).
[3]Harhausen *et al.*, J. Phys. D: Appl. Phys. **48**, 045203 (2015).

SESSION RR3: DISCHARGES IN LIQUIDS II
Thursday Morning, 13 October 2016
Room: 2b at 11:00

Contributed Papers

11:00

RR3 1 Discharge processes in a laser ablation-induced cavitation bubble K. SASAKI, Y. TAKAHASHI, *Hokkaido University* The cavitation bubble is not a static bubble but has the dynamics of expansion, shrinkage, and collapse. In this work, we tried to produce electrical discharge in a cavitation bubble which was induced by laser ablation of a titanium target in water. We placed a needle electrode at a distance of 0.5 mm from the gas-liquid boundary of the cavitation bubble at the maximum size. The electrode was connected to a high-voltage pulsed power supply. The temporal variation of the bubble size was measured by shadowgraph imaging using a high-speed camera. The high-speed camera also captured the optical emission image from the discharge. At 50 μs after applying a pulsed high voltage, we observed the formation of a swelling from the cavitation bubble. The swelling was lengthened toward the needle electrode. We observed the electrical discharge between the needle electrode and the target when they are connected by the cavitation bubble and its swelling. It is noted that both the directions of the swelling lengthening and the discharge channel are perpendicular to the gas-liquid boundary of the cavitation bubble, suggesting that the electric field is perpendicular to the gas-liquid boundary because of the existence of movable electrical charges.

11:15

RR3 2 Preparation of silver-carbon nanotubes composites with plasma electrochemistry OLIVER HOEFFT, LARA LOHMANN, MARK OLSCHEWSKI, FRANK ENDRES, *Institute of Electrochemistry, Clausthal University of Technology* Plasma electrochemistry is a powerful tool to generate free nanoparticles in aqueous solutions and especially in ionic liquids (ILs) [1,2]. Due to their very low vapour pressure, ionic liquids can be employed under vacuum conditions as fluid substrates or solvents. Thus, ionic liquids are well suitable electrolytes for plasma electrochemical processes delivering stable and homogeneous plasmas. We have shown that free copper and germanium nanoparticles can be obtained in ILs by applying a plasma as a mechanically contact-free electrode [2]. Here we present our results using an argon plasma for the electrochemical synthesis of silver on pure and pre-treated multiwall carbon nanotubes (MWCNTs) in 1-ethyl-3-methylimidazolium dicyanamide. For the pre-treatment of the MWCNTS we have used a dielectric barrier discharge plasma (DBD) at atmospheric pressure. For the untreated MWCNTs we have found a formation of free silver nanoparticles between, on and in the vicinity of the carbon nanotubes. In case of the plasma treated MWCNTs a silver-carbon nanotubes composite is formed. Thus, the treatment of the MWCNTs obviously has a great influence on the deposit. Therefore we additionally have investigated the influence of the DBD on the chemical composition of the MWCNTs surface with X-Ray Photoelectron Spectroscopy.

[1]R. Akolkar and R. M. Sankaran, J. Vac. Sci. Technol. A **31**, 050811 (2013).
[2]N. Spitczok, V. Brisinski, O. Höfft, and Frank Endres, J. Mol. Liquids **192**, 59 (2014).

11:30

RR3 3 Underwater electrical discharge in plate to plate configuration* VITALIY STELMASHUK, *Institute of Plasma Physics of the Czech Academy of Sciences* Two main configurations of high voltage electrodes submersed in water have been used for an electrical discharge generation: pin to pin and pin to plate. An electrical breakdown between plate electrodes is generally difficult to reproduce, because there is a uniform and weak electric field. One major advantage of using plate electrodes is their greater "wear hardness" to high-energy discharges. The plate electrodes can withstand extremely high energy deposition at which the pin electrode is quickly destroyed. The electrical discharge between plate electrodes can be initiated by creating an inhomogeneity in the electrical field. Two methods of discharge initiation between plate electrodes are proposed for this aim: 1) focusing of a shock wave in the inter-electrode region; 2) a bubble injection into the electrode gap. The shock wave creates favourable conditions for the electrical breakdown between the two plate electrodes: it causes that numerous microbubbles of dissolved air start to grow and serve as locations for streamer initiation. In the second method the gas bubble is injected from the one of the electrodes, which has a gas inlet hole on the lateral face for this purpose. A "volcano" like morphology of positive streamers are observed in the experiments with weak electric field.

*The authors are grateful to MEYS grant INGO LG 15013.

11:45
RR3 4 Development and Applications of discharges generated in liquids with short high voltage pulses JUERGEN KOLB, CAMELIA MIRON, ANGELA KRUTH, *Leibniz Institute for Plasma Science and Technology* MICHAL BALCERAK, MICHAL BONISLAWSKI, MARCIN HOLUB, *West Pomeranian University of Technology* Discharges that are generated within a liquid have been of scientific interest for more than a century. The possibility for a breakdown development that is not mediated by an initial gaseous phase is still disputed. In this respect are especially discharges that are instigated with short high voltage pulses calling for attention. Associated with this specific excitation scheme is a change in plasma development, plasma parameters and reaction mechanisms in the liquid. We have compared discharges in a point-to-plane geometry that were generated with 50-us or 10-ns high voltage pulses. Time-resolved shadowgraphy and spectroscopy were performed to evaluate discharge structures, plasma parameter and reactive species that were formed in distilled water or ethanol. Different propagation modes, with velocities of 6.7 km/s for tree-like streamers and only 50 m/s for bush-like streamers, were observed. Optical emission spectroscopy has shown the formation of molecular bands of nitrogen, as well as strongly broadened atomic hydrogen and oxygen, which are likely to be responsible for the observed surface modifications of polymers. With nanosecond high voltage pulses we found an increase of unsaturated bondings for polyimide surfaces that were exposed in the discharge volume.

12:00
RR3 5 Computational investigations of streamers in a single bubble suspended in distilled water under atmospheric pressure conditions* ASHISH SHARMA, DMITRY LEVKO, LAXMINARAYAN RAJA, *University of Texas at Austin* We present a computational model of nanosecond streamers generated in helium bubbles immersed in distilled water at the atmospheric pressure conditions. The model is based on the self-consistent, multispecies and the continuum description of plasma and takes into account the presence of water vapor in the gas bubble for a more accurate description of the kinetics of the discharge. We find that the dynamic characteristics of the streamer discharge are completely different at low and high over voltages. We observe that the polarity of the trigger voltage has a substantial effect on initiation, transition and evolution stages of streamers with the volumetric distribution of species in the streamer channel much more uniform for negative trigger voltages due to the presence of multiple streamers. We also find that the presence of water vapor significantly influences the distribution of the dominant species in the streamer trail and has a profound effect on the flux of the dominant species to the bubble wall.

*The research reported in this publication was supported by Competitive Research Funding from King Abdullah University of Science and Technology (KAUST).

12:15
RR3 6 Oxygen reduction reaction on highly-durable Pt/nanographene fuel cell catalyst synthesized employing in-liquid plasma TOMOKI AMANO, HIROKI KONDO, KEIGO TAKEDA, KENJI ISHIKAWA, *Nagoya University* HIROYUKI KANO, *NU Eco Engineering, Co., LTD.* MINEO HIRAMATSU, *Meijo University* MAKOTO SEKINE, MASARU HORI, *Nagoya University* We recently have established ultrahigh-speed synthesis method of nanographene materials employing in-liquid plasma, and reported high durability of Pt/nanographene composites as a fuel cell catalyst. Crystallinity and domain size of nanographene materials were essential to their durability. However, their mechanism is not clarified yet. In this study, we investigated the oxygen reduction reaction using three-types of nanographene materials with different crystallinity and domain sizes, which were synthesized using ethanol, 1-propanol and 1-butanol, respectively. According to our previous studies, the nanographene material synthesized using the lower molecular weight alcohol has the higher crystallinity and larger domain size. Pt nanoparticles were supported on the nanographene surfaces by reducing 8 wt% H_2PtCl_6 diluted with H_2O. Oxygen reduction current densities at a potential of 0.2 V vs. RHE were 5.43, 5.19 and 3.69 mA/cm2 for the samples synthesized using ethanol, 1-propanol and 1-butanol, respectively. This means that the higher crystallinity nanographene showed the larger oxygen reduction current density. The controls of crystallinity and domain size of nanographene materials are essential to not only their durability but also highly efficiency as catalyst electrodes.

SESSION RR4: ELECTRO-MAGNETIC INTERACTIONS WITH PLASMAS I
Thursday Morning, 13 October 2016; Room: 3 at 11:00; Bert Ellingboe, Dublin City University, presiding

Invited Papers

11:00
RR4 1 Peering inside microplasmas sustained by microwaves, millimeter waves and beyond*
JEFFREY HOPWOOD, *Tufts University*

Atmospheric microplasmas are experimentally investigated over a range of excitation frequency from 0.5 to 12 GHz. A validated fluid model correctly predicts the measured electron density in this band of operation. This model is then extended to predict plasma behavior up to 0.4 THz. At constant power (0.25 W), the central electron density increases to $5x10^{14}$ cm^{-3} as the microwave frequency increases toward the electron energy dissipation frequency of 5 GHz (in argon). Above 5 GHz, the argon plasma density remains approximately constant, but the electrode voltage decreases to less than 5 volts in amplitude. This is remarkable in that the microwave potential is less than the excitation potential of argon. In the millimeter wave band, we observe series resonance between the plasma inductance and sheath capacitance at ~30 GHz. The parallel resonance results in strong electron oscillation within the microplasma at the position where the electron plasma frequency is equal to the excitation frequency (~200 GHz). Crossing resonance boundaries changes the nature of the microplasma impedance between capacitive, resistive, and inductive. In addition to linear behavior, we also present models and measurements of microplasma nonlinearity. Nonlinearity generates harmonic plasma currents and is due primarily to dynamic sheath expansion and electron conduction currents. In total, the microplasma provides a rich variety of electromagnetic behaviors that can be incorporated into plasma-reconfigurable metamaterials and photonic crystals.

*This work was supported by the Air Force Office of Scientific Research under Award No. FA9550-14-10317 with Dr. Mitat Birkan as the program manager.

Contributed Papers

11:30

RR4 2 Abnormal glow discharge as a variable capacitor for tunable RF systems SERGEY MACHERET, ABBAS SEMNANI, DIMITRIOS PEROULIS, *Purdue University* For frequency-tunable resonators and filters in high-power applications, conventional semiconductor devices are easily damaged, while mechanically-tunable systems are bulky and slow. In this regard, weakly ionized plasmas can offer an attractive solution. In this work, an LC resonator circuit where a commercial gas discharge tube (GDT) serves as a variable capacitor was studied experimentally and theoretically. The experiments show continuous decrease of the resonant frequency by up to 50 percent with increase in the DC current through the GDT. Analysis of the current-voltage characteristic and the breakdown parameters, combined with lumped-parameter equivalent-circuit RF simulations, allowed us to determine the gas pressure, the electrode coating material and the secondary emission coefficient, and to achieve a very good agreement between the calculated and measured transmittance values. The analysis reveals that reduction in the cathode sheath thickness with increase in the DC current in the abnormal glow discharge regime is the key factor responsible for the experimentally observed tunability.

11:45

RR4 3 Numerical modeling of high power breakdown in metamaterials KONSTANTINOS KOURTZANIDIS, DYLAN PEDERSON, LAXMINARAYAN RAJA, *The University of Texas at Austin* Metamaterials consist of sub-wavelength structural inclusions layered in a periodic fashion, which provide an effective response to electromagnetic (EM) radiation. The electric or magnetic responses of these materials are based on the resonant nature of their constitutive micro-structures. Under high power EM radiation, these resonances can result in the production of high amplitude currents and field amplification. Depending on the background gas and supporting pressure, breakdown can occur. The formation of plasma can strongly modify the EM response of the metamaterial and thus a detailed study on the breakdown threshold, plasma localization and EM response modification is necessary. Here, we present three-dimensional numerical simulations of high power – high frequency air breakdown in metamaterials. We use a self-consistent fluid description of the plasma formation and dynamics coupled with Maxwell's equations via the electron momentum equation. We study two typical (for metamaterials) micro-structures: The Split Ring Resonator and the Cut Wire pairs. Breakdown threshold is identified for both configurations. Calculations of transmittance and retrieval of the metamaterials' effective parameters help us quantify the effect of plasma formation on the EM response of these metamaterials.

12:00

RR4 4 Plasma-Based Tunable High Frequency Power Limiter ABBAS SEMNANI, SERGEY MACHERET, DIMITRIOS PEROULIS, *Purdue University* Power limiters are often employed to protect sensitive receivers from being damaged or saturated by high-power incoming waves. Although wideband low-power limiters based on semiconductor technology are widely available, the options for high-power frequency-selective ones are very few. In this work, we study the application of a gas discharge tube (GDT) integrated in an evanescent-mode (EVA) cavity resonator as a plasma-based power limiter. Plasmas can inherently handle higher power in comparison with semiconductor diodes. Also, using a resonant structure provides the ability of having both lower threshold power and frequency-selective limiting, which are important if only a narrowband high-power signal is targeted. Higher input RF power results in stronger discharge in the GDT and consequently higher electron density which results in larger reflection. It is also possible to tune the threshold power by pre-ionizing the GDT with a DC bias voltage. As a proof of concept, a 2-GHz EVA resonator loaded by a 90-V GDT was fabricated and measured. With reasonable amount of insertion loss, the limiting threshold power was successfully tuned from 8.3 W to 590 mW when the external DC bias was varied from 0 to 80 V. The limiter performed well up to 100 W of maximum available input power.

12:15

RR4 5 Control of powerful microwaves using EBG plasma structures* LEANID SIMONCHIK, *Institute of Physics of NAS of Belarus* THIERRY CALLEGARI, JEROME SOKOLOFF, *University of Toulouse, Laboratory of plasma and energy conversion* MAXIM USACHONAK, *Institute of Physics of NAS of Belarus* Glow discharge plasmas have great potential for application as control elements in microwave devices designed on the basis of electromagnetic band gap (EBG) structures. In this report, a plasma control of powerful microwave propagation by means of 1D and 2D EBG structures is under investigation. Three pulsed discharges in argon (or helium) at atmospheric pressure are applied in the capacity of plasma inhomogeneities. Temporal behavior of electron concentration in discharge is determined. The transmission spectra of 1D EBG structure formed solely by plasma in the X-waveguide are measured. The amplitudes of short (~200 ns) and powerful (50 kW) microwave pulses at frequency of 9.15 GHz are strongly suppressed (more than on 40 dB) when plasma structure exists. The propagation of these powerful microwave pulses through the triangular metallic 2D EBG structure with the plasma control elements is investigated, too. It is shown that the transmission of the 2D EBG structure at the angle of 45° ceases quickly (during a few tenth of nanoseconds) when plasma acts as a compensator of defect in the front row of the structure. On the contrary, the transmission arises quickly once plasma acts as an additional defect.

*The support of BRFBR-CNRS grant F15F-004 is acknowledged.

SESSION SR1: ELECTRON-MOLECULE COLLISION DATA FOR PLASMA MODELLING

Thursday Afternoon, 13 October 2016; Room: 1 at 14:00; Alisher Kadyrov, Curtin University, presiding

Invited Papers

14:00

SR1 1 Recent results for electron scattering from biomolecules and molecules formed due to plasma treatment of biomass

MICHAEL BRUNGER, *School of Chemical and Physical Sciences, Flinders University*

We have been concentrating our recent experimental studies, for determining absolute cross sections, on both biomolecules (e.g. pyrimidine and benzoquinone) and molecules that result when biomass undergoes treatment by plasmas (e.g. phenol and furfural). All this work was supported and informed by computations from the Brazilian SMC groups and the Madrid IAM-SCAR group. A major rationale for these investigations was to provide cross section data for relevant modelling studies, and in this talk I will also present some results from those modelling studies. Possible further investigations will be canvassed in this presentation. Work done in conjunction with: D. B. Jones, L. Campbell, R. D. White, S. J. Buckman, M. A. P. Lima, M. C. A. Lopes, M. H. F. Bettega, M. T. do N. Varella, R. F. da Costa, G. García, P. Limão-Vieira, D. H. Madison, O. Ingólfsson and many other friends and colleagues.

14:30

SR1 2 R-matrix calculations of electron molecule collision data for plasma models

JONATHAN TENNYSON, *University College London*

Models of low-pressure plasma require electron collision cross sections for many processes. For transient molecular species, almost none of these data are available from laboratory measurements so theory has to be the chosen means of providing the necessary information. The R-matrix method is a well-established fully quantal procedure for computing low-energy electron-collision cross sections. The R-matrix calculations using the UK Molecular R-matrix codes (UKRMol) [1], which are run by the Quantemol-N expert system, are being employed to provide a wide range of collision cross sections. These are augmented by use of suitable high-energy approximations, such as BEB for ionisation, and a novel procedure to give branching ratios for the fragmentation pattern following electron impact ionisation and electron impact dissociation. Examples, such as recently generated complete cross section sets for the molecules NF, NF and NF [2], will be given at the meeting.

[1]J. M. Carr *et al.*, Euro J. Phys. D 58 (2016).

[2]J. R. Hamilton, J. Tennyson, S. Huang, and M. J. Kushner, in Preparation for Submission to Plasma Sci. Sources Tech. (2016).

Contributed Papers

15:00

SR1 3 Electron transport in furfural: dependence of the electron ranges on the cross sections and the energy loss distribution functions L. ELLIS-GIBBINGS, K. KRUPA, *Consejo Superior de Investigaciones Científicas* R. COLMENARES, *Hospital Universitario Ramón y Cajal* F. BLANCO, *Universidad Complutense de Madrid* A. MUÑOZ, *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas* M. MENDES, F. FERREIRA DA SILVA, P. LIMÁ VIEIRA, *Universidade Nova de Lisboa* D. B. JONES, M. J. BRUNGER, *Flinders Univ* G. GARCÍA, *Consejo Superior de Investigaciones Científicas* Recent theoretical and experimental studies have provided a complete set of differential and integral electron scattering cross section data from furfural over a broad energy range [1,2]. The energy loss distribution functions have been determined in this study by averaging electron energy loss spectra for different incident energies and scattering angles. All these data have been used as input parameters for an event by event Monte Carlo simulation procedure to obtain the electron energy deposition patterns and electron ranges in liquid furfural. The dependence of these results on the input cross sections is then analysed to determine the uncertainty of the simulated values.

[1]D. B. Jones, R. F. da Costa, M. T. do N. Varella, M. H. F. Bettega, M. A. P. Lima, F. Blanco, G. García, and M. J. Brunger, J. Chem. Phys. **144**, 144303 (2016).

[2]R. F. da Costa, M. T. do N. Varella, M. H. F. Bettega, R. F. C. Neves, M. C. A. Lopes, F. Blanco, G. García, D. B. Jones, M. J. Brunger, and M. A. P. Lima, J. Chem. Phys. **144**, 124310 (2016).

15:15

SR1 4 Plasma recombination in hydrocarbons and hydrocarbon:oxygen mixtures after high-voltage nanosecond discharge EUGENE ANOKHIN, MAXIM POPOV, *Moscow Institute of Physics and Technology* IGOR KOCHETOV, *Triniti* ANDREY STARIKOVSKIY, *Princeton University* NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY TEAM, TRINITY TEAM, PRINCETON UNIVERSITY TEAM The results of the experimental and numerical study of high-voltage nanosecond discharge afterglow in pure ethane, propane and hydrocarbon:oxygen mixtures are presented for room temperature and pressures from 2 to 20 Torr. Time-resolved electron density during the plasma decay was measured with a microwave interferometer for initial electron densities in the range between 5×10^{10} and 3×10^{12} cm^{-3} and the effective recombination coefficients were obtained. Measured effective recombination coefficients increased with gas pressure and were much higher than the recombination coefficients for simple molecular hydrocarbon ions. Synergistic effect was observed in hydrocarbon:oxygen mixtures when the recombination rates in the mixtures were higher than those in pure hydrocarbon and in pure oxygen. Calculations showed that electrons had time to thermalize prior to the recombination in hydrocarbon-containing plasma. The measured data were interpreted under the assumption that cluster hydrocarbon ions are formed during the plasma decay that is controlled by the dissociative electron recombination with these ions at electron room temperature.

SESSION SR2: INDUCTIVELY COUPLED PLASMAS II

Thursday Afternoon, 13 October 2016
Room: 2a at 14:00
Jean Paul Booth, Ecole Polytechnique, presiding

Contributed Papers

14:00

SR2 1 Simulating industrial plasma reactors - A fresh perspective* SEBASTIAN MOHR, SARA RAHIMI, *Quantemol* JONATHAN TENNYSON, *University College London* OLIVER ANSELL, JASH PATEL, *SPTS Technologies* A key goal of the presented research project PowerBase is to produce new integration schemes which enable the manufacturability of 3D integrated power smart systems with high precision TSV etched features. The necessary high aspect ratio etch is performed via the BOSCH process. Investigations in industrial research are often use trial and improvement experimental methods. Simulations provide an alternative way to study the influence of external parameters on the final product, whilst also giving insights into the physical processes. This presentation investigates the process of simulating an industrial ICP reactor used over high power (up to 2x5 kW) and pressure (up to 200 mTorr) ranges, analysing the specific procedures to achieve a compromise between physical correctness and computational speed, while testing commonly made assumptions. This includes, for example, the effect of different physical models and the inclusion of different gas phase and surface reactions with the aim of accurately predicting the dependence of surface rates and profiles on external parameters in SF6 and C4F8 discharges.

*This project has received funding from the Electronic Component Systems for European Leadership Joint Undertaking under Grant Agreement No. 662133 PowerBase.

14:15

SR2 2 A hybrid model of biased inductively coupled discharges[1] DEQI WEN, *Dalian University of Technology* MICHAEL A LIEBERMAN, *Uniersity of California, Berkeley* QUANZHI ZHANG, *University of Anterwerp* YONGXIN LIU, YOUNIAN WANG, *Dalian University of Technology* A hybrid model, i.e. a global model coupled bidirectionally with a parallel Monte-Carlo collision (MCC) sheath model, is developed to investigate an inductively coupled discharge with a bias source. To validate this model, both bulk plasma density and ion energy distribution functions (IEDFs) are compared with experimental measurements in an argon discharge, and a good agreement is obtained. On this basis, the model is extended to weakly electronegative Ar/O_2 plasma. The ion energy and angular distribution functions versus bias voltage amplitude are examined. The different ion species (Ar^+, O_2^+, O^+) have various behaviors because of the different masses. A low bias voltage, Ar^+ has a single energy peak distribution and O^+ has a bimodal distribution. At high bias voltage, the energy peak separation of O^+ is wider than Ar^+. [1]This work has been supported by the National Nature Science Foundation of China (Grant No. 11335004) and Specific project (Grant No 2011X02403-001) and partially supported by Department of Energy Office of Fusion Energy Science Contract DE-SC000193 and a gift from the Lam Research Corporation.

14:30

SR2 3 Modeling of inductively coupled plasmas at low pressure conditions SOTIRIS MOUCHTOURIS, GEORGE KOKKORIS, *Institute of Nanoscience and Nanotechnology, NCSR Demokritos* PLASMA GROUP TEAM Low pressure inductively coupled plasmas are simulated with a hybrid plasma model [1] which couples fluid with Maxwell's equations and a Monte Carlo (MC) particle tracing model for the calculation of the ion mobility in the sheaths. The case study is Ar plasma in the GEC reference cell. Instead of using a MC model for the calculation of the electron energy distribution function (EEDF), a generalized EEDF is formulated; it depends on the local plasma potential and captures the deviations from the Maxwellian EEDF at low pressure conditions [2]. The model results are compared with spatially resolved measurements [3] of electron density, electron temperature, plasma potential, and ion current density on the wafer at different power and pressure conditions. Additionally, the ion energy and angular distributions on the wafer are calculated by a MC model and validated by a comparison with experimental measurements.

[1]S. Mouchtouris and G. Kokkoris, Plasma Sources Sci. Technol. **25**, 025007 (2016).
[2]V. A. Godyak, R. B. Piejak, and B. M. Alexandrovich, Plasma Sources Sci. Technol. **11**, 525 (2002).
[3]P. A. Miller, G. A. Hebner, K. E. Greenberg, P. D. Pochan, and B. P. Aragon, J. Res. Natl Inst. Stand. Technol. **100**, 427 (1995).

14:45

SR2 4 Structure Control of Vertical Nanographene toward Electrochemical and Bio Applications MINEO HIRAMATSU, *Meijo University* HIROKI KONDO, MASARU HORI, *Nagoya University* Carbon nanowalls (CNWs) as platform based on vertical nanographene with large surface area offer great promise for providing emerging applications such as nanostructured electrodes for electrochemical sensing, biosensing, energy conversion, and scaffold for cell culturing. CNWs are composed of few-layer graphene standing almost vertically on the substrate, forming a self-supported network of maze-like wall structures. From a practical viewpoint, the structures of CNWs including spacing between adjacent nanowalls, nanowall height, thickness of individual nanowall, crystallinity and alignment should be controlled according to the usage of CNWs. The morphologies of CNWs depend on source gases, pressure, process temperature as well as the type of plasma used for the growth. In this study, CNWs were synthesized using inductively coupled plasma (ICP) employing methane/hydrogen/argon system.We investigated systematically the effects of ions incident upon the substrate, radical flow, and catalytic metals on the change of CNW morphologies. We report the current status of the control of CNW structures by the control of ions and radicals during the growth process as well as nucleation control, together with examples of electrochemical applications using CNWs.

15:00

SR2 5 Research on the mechanism of multiple inductively coupled plasma source for large area processing JANGJAE LEE, SI-JUN KIM, *Department of physics, Chungnam National University* DAEWOONG KIM, *Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology* KWANGKI KIM, YOUNGSEOK LEE, SHINJAE YOU,* *Department of physics, Chungnam National University* In the plasma processing, inductively coupled plasma having the high-density is often used for high productivity. In large area plasma processing, the plasma can be generated by using the multi-pole connected in parallel. However, in case of this, it is difficult for power to be transferred to plasma uniformly. To solve the problem, we studied the mechanism of inductively coupled plasma connected in parallel. By using the transformer model, the multiple ICP source is treated. We also studied about the change of the plasma parameters over the time through the power balance equation and particle balance equation.

*Corresponding author.

15:15
SR2 6 Synthesis of Silicon Nanoparticles in Inductively Coupled Plasmas* ARAM H. MARKOSYAN, *University of Michigan* ROMAIN LE PICARD, STEVEN L. GIRSHICK, *University of Miinesota* MARK J. KUSHNER, *University of Michigan* The synthesis of silicon nanoparticles (Si-NPs) is being investigated for their use in photo-emitting electronics, photovoltaics, and biotechnology. The ability to control the size and mono-disperse nature of Si-NPs is important to optimizing these applications. In this paper we discuss results from a computational investigation of Si-NP formation and growth in an inductively coupled plasma (ICP) reactor with the goal of achieving this control. We use a two dimensional numerical model where the algorithms for the kinetics of NP formation are self-consistently coupled with a plasma hydrodynamics simulation [1]. The reactor modeled here resembles a GEC reference cell through which, for the base case, a mixture of Ar/SiH_4 =70/30 flows at 150 sccm at a pressure of 100 mTorr. In continuous wave mode, three coils located on top of the reactor deliver 150 W. The electric plasma potential confines negatively charged particles at the center of the discharge, increasing the residence time of negative NPs, which enables the NPs to potentially grow to large and controllable sizes of many to 100s nm. We discuss methods of controlling NP growth rates by varying the mole fraction and flow rate of SiH_4, and using a pulsed plasma by varying the pulse period and duty cycle.

*Work supported by DOE Office of Fusion Energy Science and National Science Foundation.

[1]R. Le Picard, A. H. Markosyan, D. Porter, S. L. Girshick, and M. J. Kushner, Plasma Chem. Plasma Proc. **36**, 941 (2016).

SESSION SR3: BIOLOGICAL APPLICATIONS OF PLASMA I
Thursday Afternoon, 13 October 2016; Room: 2b at 14:00; Mounir Laroussi, Old Dominion University, presiding

Invited Papers

14:00
SR3 1 The Synergistic Effect between Electrical and Chemical Factors in Plasma Gene/Molecule-Transfection*
MASAFUMI JINNO, *Ehime University*

This study has been done to know what kind of factors in plasma and processes on cells promote plasma gene/molecule transfection. We have discovered a new plasma source using a microcapillary electrode which enables high transfection efficiency and high cell survivability simultaneously. However, the mechanism of the transfection by plasma was not clear. To clarify the transfection mechanisms by micro plasma, we focused on the effects of electrical (current, charge, field, etc.) and chemical (radicals, RONS, etc.) factors generated by the micro plasma and evaluated the contribution weight of three groups of the effects and processes, i.e. electrical, chemical and biochemical ones. At first, the necessity of the electrical factors was estimated by the laser produced plasma (LPP). Mouse L-929 fibroblast cell was cultured on a 96-well plate or 12-well micro slide chamber. Plasmids pCX-EGFP in Tris-EDTA buffer was dropped on the cells and they were exposed to the capillary discharge plasma (CDP) or the LPP. In the case of the CDP, the plasma was generated between the tip of the capillary electrode and the cells so that both electrical and chemical factors were supplied to the cells. In this setup, about 20% of average transfection efficiency was obtained. In the case of the LPP, the plasma was generated apart from the cells so that electrical factors were not supplied to the cells. In this setup, no transfection was observed. These results show that the electrical factors are necessary for the plasma gene transfection. Next, the necessity of the chemical factors was estimated the effect of catalase to remove H_2O_2 in CDP. The transfection efficiency decreased to 0.4 by scavenging H_2O_2 with catalase. However, only the solution of H_2O_2 caused no gene transfection in cells. These results shows that H_2O_2 is important species to cause gene/molecule transfection but still needs a synergistic effect with electrical or other chemical factors.

*This work was partly supported by Grants-in-Aid for Scientific Research (25108509 and 15H00896) from JSPS and a grant from Ehime University. The plasmids are prepared by ADRES Shigenobu of Ehime University.

Contributed Papers

14:30
SR3 2 Calcium oxalate syntheses in a solution containing glucose by the atmospheric pressure plasma irradiation NAOYUKI KURAKE, HIROMASA TANAKA, KENJI ISHIKAWA, KAE NAKAMURA, HIROAKI KAJIYAMA, FUMITAKA KIKKAWA, MASAAKI MIZUNO, *Nagoya University* YOKO YAMANISHI, *Kyusyu University* MASARU HORI, *Nagoya University* The non-equilibrium atmospheric pressure plasma (NEAPP) has been attracted attention because of its characteristic high reactivity even in a low temperature so that various phenomena by the NEAPP such as a sterilization, growth promotion and so forth have been reported around the world. Previously, we reported the NEAPP irradiation generated the calcium oxalate crystals in the medium, which contains 31 kinds of organics and inorganics. The Dulbecco's

Modified Eagle Medium (DMEM) which was used in previous study is composed of no oxalate. Interestingly, not only crystallization but also synthesis of the oxalate was occurred by the NEAPP irradiation. Also the crystallization details were analyzed with the X-ray diffraction (XRD). In this study, we have clarified the mechanism on the crystallization due that D-glucose, calcium ion and bicarbonate ions are minimum essential components. The oxalate synthesis was proved by the gas chromatography and mass spectrometer (GC-MS). Finally, we conclude that a supersaturation of oxalic acid synthesized in those 3 species by the NEAPP.

14:45

SR3 3 Numerical simulation of the generation of reactive oxygen and nitrogen species (RONS) in water by atmospheric-pressure plasmas and their effects on Escherichia coli (E. coli)* KAZUMASA IKUSE, SATOSHI HAMAGUCHI, *Osaka Univ* We have used two types of numerical simulations to examine biological effects of reactive oxygen and nitrogen species (RONS) generated in water by an atmospheric-pressure plasma (APP) that irradiates the water surface. One is numerical simulation for the generation and transport of RONS in water based on the reaction-diffusion-advection equations coupled with Poisson equation. The rate constants, mobilities, and diffusion coefficients used in the equations are obtained from the literature. The gaseous species are given as boundary conditions and time evolution of the concentrations of chemical species in pure water is solved numerically as functions of the depth in one dimension. Although it is not clear how living organisms respond to such exogenous RONS, we also use numerical simulation for metabolic reactions of Escherichia coli (E. coli) and examine possible effects of such RONS on an *in-silico* model organism. The computation model is based on the flux balance analysis (FBA), where the fluxes of the metabolites in a biological system are evaluated in steady state, i.e., under the assumption that the fluxes do not change in time. The fluxes are determined with liner programming to maximize the growth rate of the bacteria under the given conditions. Although FBA cannot be directly applied to dynamical responses of metabolic reactions, the simulation still gives insight into the biological reactions to exogenous chemical species generated by an APP.

*Partially supported by JSPS Grants-in-Aid for Scientific Research.

15:00

SR3 4 Plasma treatment of Seeds: effect on growth, spores and bacterial charge* P. F. AMBRICO, *CNR Nanotec, Bari* M. SIMEK, *IPP, CAS, Prague* M. MORANO, *CRSFA, Locorotondo (BA)* M. AMBRICO, *CNR Nanotec, Bari* A. MINAFRA, *CNR, IPSP, Bari* V. PRUKNER, *IPP, CAS, Prague* R. M. DE MICCOLIS ANGELINI, P. TROTTI, *DiSSPA, Univ. Bari* We report on the effect of low temperature plasma treatment on tomato, basil and tobacco commercial seeds. Seeds were treated in filtered ambient air volume, surface and plasma jet DBD at atmospheric pressure Sterile agar substrate, supplemented with a nutrient and vitamin mixture, was used to allow seeds germination in sterilized sealed plastic containers. The seeds were stored in controlled environmental condition (T = 26C, cycle of 14hrs light/10hrs dark condition). Since all the procedure was performed under sterile conditions, only bacteria and fungi carried by seeds could grow. Plasma treatment significantly reduced the presence of bacterial contamination, while some fungi could resist at shortest exposures Seeds germination was then followed by time lapse photography in sterile water on 3MM Whatman paper in a closed container. The effect of plasma treatment was a faster germination time of seeds and emergence of cotyledons, able to start photosynthesis in seedlings.The plasma treated seeds were also sow in a soil/peat moss mixture. Plants were cultivated for about 40 days, showing that plasma induced a faster growth in length and weight with respect to untreated seeds.Furthermore the effect of plasma on seeds surface was studied by SEM imaging.

*We acknowledge 'SELGE' (Puglia) and TACR (TA03010098).

15:15

SR3 5 It's all about NO? – The role of NO and its derivates produced by a DBD in air for wound healing* K. STAPELMANN, F. KOGELHEIDE, S. BALDUS, J.-W. LACKMANN, P. AWAKOWICZ, K. KARTASCHEW, M. HAVENITH, D. SCHROEDER, V. SCHULZ-VON DER GATHEN, *Ruhr University Bochum* C. OPLAENDER, C.V. SUSCHEK, *Heinrich Heine University Duesseldorf* DBDs can be used therapeutically in various clinical applications [1], e.g. improving the wound healing [2]. Besides the disinfecting properties of plasma [3], tissue exposed to plasma responds to the highly reactive mixture of RONS [4]. In particular NO plays an essential role in skin physiology, e.g. promoting wound healing and influencing the microcirculation. However, not only NO itself but also NO-derivates (NOD), such as nitrite and nitrosothiols, play an essential role, acting as NO-storage under acidic conditions and thus contributing to NO bioavailability with a long-term effect. Selected results of the DFG package project PlaCID (Plasma-Cell-Interaction in Dermatology) are presented. Spatial and time-resolved characterization of the DBD regarding n_e, O (TALIF) and O_3 (OAS) densities is shown. Single skin components investigated with Raman and FTIR spectroscopy show distinct modifications caused by RONS. From single components to whole skin, we investigated diffusion of NO through intact epidermis and dermal enrichment with NOD, acting as long-term storage for NO bioavailability.

*Funding from the DFG within PAK816 is gratefully acknowledged.

[1] S. Emmert *et al.*, Clin. Plasma Med. **1**, (2013).
[2] F. Brehmer *et al.*, JEADV **29**, (2015).
[3] A. Helmke *et al.*, Recent Pat. Antiinfect. Drug Discov, (2012).
[4] K. Heuer *et al.*, Nitric Oxide **44**, (2015).

SESSION SR4: ELECTRO-MAGNETIC INTERACTIONS WITH PLASMAS II

Thursday Afternoon, 13 October 2016
Room: 3 at 14:00
Julian Schulze, Ruhr University, presiding

Contributed Papers

14:00

SR4 1 Extinction of 10.6 μm laser radiation by free electrons in an argon filamentary discharge at atmospheric pressure S.H. PARK, H.J. YANG, A.E. MIRONOV, S.-J. PARK, J.G. EDEN, *Department of Electrical and Computer Engineering, University of Illinois Urbana Champaign* Experiments will be described in which the extinction of 10.6 μm photons by free electrons in a single filamentary discharge is being studied. The extinction ranges from 3 to 10 percent over a path length of 1 cm, depending on the argon flow rate. The temporally- and spatially-averaged electron density in the filament is approximately 10^{15} cm^{-3}, as determined by Stark broadening of the hydrogen alpha (656.28 nm) and argon I (696.54 nm) lines. Calculations indicate that the observed extinction of 10.6 μm is attributable to a combination of inverse bremsstrahlung and a negative lens effect, and experimental results will be compared to theoretical calculations based on Boltzmann's equation. The potential application of such high electron density plasmas to studies of fundamental plasma phenomena, as well as optical applications will be discussed.

14:15

SR4 2 Generation conditions of CW Diode Laser Sustained Plasma KOJI NISHIMOTO, MAKOTO MATSUI, TAKAHIRO ONO, *Shizuoka University* Laser sustained plasma was generated using 1 kW class continuous wave diode laser. The laser beam was focused on the seed plasma generated by arc discharge in 1 MPa xenon lamp. The diode laser has advantages of high energy conversion efficiency of 80%, ease of maintenance, compact size and availability of conventional quartz based optics. Therefore, it has a prospect of further development compared with conventional CO2 laser. In this study, variation of the plasma shape caused by laser power is observed and also temperature distribution in the direction of plasma radius is measured by optical emission spectroscopy.

14:30

SR4 3 Nanosecond-timescale high-pressure gas discharge in a microwave pulse compressor* ANATOLI SHLAPAKOVSKI, LEONID BEILIN, YAKOV KRASIK, *Physics Department, Technion* The results of experimental and numerical studies of the microwave plasma discharge initiated by a nanosecond laser pulse are presented. The discharge is ignited in the pressurized gas filling the switch, which opens the charged resonant cavity, so that the accumulated microwave energy is rapidly released into a load. Fast-framing optical imaging showed that the plasma in the switch appears as filaments expanding along the RF electric field. The temporal evolution of the plasma density was derived from time-resolved spectroscopic measurements. With increasing microwave energy in the cavity, the plasma appears earlier in time after the laser beam enters the switch and its density rises more steeply reaching values which exceed 10^{16} cm^{-3} at a gas pressure of $2 \cdot 10^5$ Pa. Numerical simulations were conducted using the gas conductivity model of plasma and representation of discharge origin by setting initial population of seed electrons treated by PIC algorithm. The results showed good agreement with the experiments and explained how the self-consistent dynamics of the plasma and RF fields determines the quality of microwave output pulses. In addition, the dynamics of the microwave energy absorption in the discharge plasma was studied. It was shown that at a high pressure, even with an unlimited rate of ionization, a significant portion of the stored energy, ≈20%, is lost.

*This work was partially supported by the BSF Grant No. 2012038.

14:45

SR4 4 Ionization processes in combined high-voltage nanosecond – laser discharges in inert gas ANDREY STARIKOVSKIY, MIKHAIL SHNEIDER, *Princeton University* PU TEAM Remote control of plasmas induced by laser radiation in the atmosphere is one of the challenging issues of free space communication, long-distance energy transmission, remote sensing of the atmosphere, and standoff detection of trace gases and bio-threat species. Sequences of laser pulses, as demonstrated by an extensive earlier work, offer an advantageous tool providing access to the control of air-plasma dynamics and optical interactions. The avalanche ionization induced in a pre-ionized region by infrared laser pulses where investigated. Pre-ionization was created by an ionization wave, initiated by high-voltage nanosecond pulse. Then, behind the front of ionization wave extra avalanche ionization was initiated by the focused infrared laser pulse. The experiment was carried out in argon. It is shown that the gas pre-ionization inhibits the laser spark generation under low pressure conditions.

SESSION TR1: LASER-BASED DIAGNOSTICS II
Thursday Afternoon, 13 October 2016; Room: 1 at 16:00; Edward Barnat, Sandia National Laboratories, presiding

Invited Papers

16:00

TR1 1 Measurements of the momentum flux from a low-temperature plasma to a surface*
THOMAS TROTTENBERG, *Institute of Experimental and Applied Physics, University of Kiel*

The forces that low-temperature plasmas exert on surfaces in contact with the plasma have never been a significant topic. The reason might be the smallness of such forces and the expected difficulties in their measurement. Therefore, only in cases of special plasmas which were designed for the generation of directed momentum (in particular electric space propulsion), force measurements have been reported [1]. Recently, our group demonstrated that the forces related to plasma-wall interactions are experimentally accessible with some effort [2]. This presentation overviews our experimental approaches in the design of force measuring probes and reports on recent measurements with probes that have been integrated into a plane wall. The observations and prospects for an application as novel plasma diagnostic [3] are discussed.

*This work was financially supported by the German Aerospace Center (DLR) under grant agreement 50 RS 1301.

[1] G. Makrinich and A. Fruchtman, Phys. Plasmas **21**, 023505 (2014).
[2] Th. Trottenberg, Th. Richter, and H. Kersten, Eur. Phys. J. D **69**, 91 (2015).
[3] U. Czarnetzki and T. V. Tsankov, Eur. Phys. J. D **69**, 236 (2015).

Contributed Papers

16:30

TR1 2 Thomson Scattering of Plasma Turbulence in PSI-2 MICHAEL HUBENY, BERND SCHWEER, *Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung—Plasmaphysik, 42425 Jülich* DIRK LUGGENHÖLSCHER, UWE CZARNETZKI, *Institut für Plasma und Atomphysik, Ruhr-Universität Bochum, 44780 Bochum* BERNHARD UNTERBERG, *Forschungszentrum Jülich GmbH, Institut für Energie- und*

Klimaforschung—Plasmaphysik, 42425 Jülich Linear plasma devices are widely used to study fundamental plasma characteristics and to simulate particle and heat loads representing first wall/divertor conditions of fusion reactors. In high power discharges at PSI-2 the plasma edge exhibits turbulence with intermittent transport events. The combination of Thomson Scattering by a photon counting method and a fast framing CMOS camera in conjunction with conditional averaging gives access to the evolution of density and temperature profiles during transient plasma dynamics. Radial density and temperature profiles in Ar, D_2, He and Ne discharges were measured and compared with existing diagnostics. In high power, low gas-feed Argon discharges the dominating m=1 rotation was found to correspond to a 20% Te fluctuation amplitude around the temporal mean at the profile maxima. In the edge of D_2 discharges transients are selected by conditional averaging and a significant temperature increase was found in the edge of TS profiles upon ejection accompanied by a 20% drop in bulk density.

16:45

TR1 3 Experimental determination of the wavelength of the instability developing over the gas-vacuum interface of a supersonic annular flow TAL QUELLER, EYAL KROUPP, DAVID NAIMARK, YITZHAK MARON, *Faculty of Physics, Weizmann Institute of Science* In the present experimental work the instability wavelength of the boundary between a supersonic annular gas puff flow, and the ambient vacuum was measured using two-dimensional interferometry. An annular De-Laval nozzle connected to a fast valve was used in order to create the supersonic flow. The interference pattern of the laser beam traversing the boundary was projected onto a large format CCD, resulting in a high spatial resolution (30 um). An ultra-fast mechanical shutter enabled the rapid exposure of the beam, resulting in a high temporal resolution (3 us). These resolutions were necessary in order to enable the observation of the quasi-periodic structure of the boundary. The fact that this structure was not observable when using lower resolutions, enables us to set an upper limit on the wavelength of the instability in the flow edge and a lower limit on the time scale in which this instability wavelength travels. The knowledge of these gas-puff flow parameters can be used for setting more realistically the initial boundary conditions in computer simulations that attempt to study, e.g., the implosion of a plasma cylinder and other processes developing around a gas-vacuum interface of a supersonic flow.

17:00

TR1 4 Polarization resolved electric field measurements on plasma bullets in N_2 using four-wave mixing MARC VAN DER SCHANS, *Eindhoven University of Technology, Department of Applied Physics* PATRICK BOEHM, *Ruhr-University Bochum, Institute for Experimental Physics V* SANDER NIJDAM, *Eindhoven University of Technology, Department of Applied Physics* WILBERT IJZERMAN, *Philips Lighting* UWE CZARNETZKI, *Ruhr-University Bochum, Institute for Experimental Physics V* Atmospheric pressure plasma jets generated by kHz AC or pulsed DC voltages typically consist of discrete guided ionization waves called plasma bullets. In this work, the electric field of plasma bullets generated in a pulsed DC jet with N_2 as feed gas is investigated using the four-wave mixing method. In this diagnostic two laser beams, where one is Stokes shifted from the other, non-linearly interact with the N_2 molecules and the bullet's electric field. As a result of the interaction a coherent anti-Stokes Raman scattered (CARS) beam and an infrared beam are generated from which the electric field can be determined. Compared to emission-based methods, this technique has the advantage of being able to also probe the electric field in regions around the plasma bullet where no photons are emitted. The four-wave mixing method and its analysis have been adapted to work with the non-uniform electric field of plasma bullets. In addition, an ex-situ calibration procedure using an electrode geometry different from the discharge geometry has been developed. An experimentally obtained radial profile of the axial electric field component of a plasma bullet in N_2 is presented. The position of this profile is related to the location of the propagating bullet from temporally resolved images.

17:15

TR1 5 Stark spectroscopy of atomic hydrogen balmer-alpha line for electric field measurement in plasmas by saturation spectroscopy S. NISHIYAMA, K. KATAYAMA, *Hokkaido University* H. NAKANO, M. GOTO, *National Institute for Fusion Science* K. SASAKI, *Hokkaido University* Detailed structures of electric fields in sheath and pre-sheath regions of various plasmas are interested from the viewpoint of basic plasma physics. Several researchers observed Stark spectra of Doppler-broadened Rydberg states to evaluate electric fields in plasmas; however, these measurements needed high-power, expensive tunable lasers. In this study, we carried out another Stark spectroscopy with a low-cost diode laser system. We applied saturation spectroscopy, which achieves a Doppler-free wavelength resolution, to observe the Stark spectrum of the Balmer-alpha line of atomic hydrogen in the sheath region of a low-pressure hydrogen plasma. The hydrogen plasma was generated in an ICP source which was driven by on-off modulated rf power at 20 kHz. A planar electrode was inserted into the plasma. Weak probe and intense pump laser beams were injected into the plasma from the counter directions in parallel to the electrode surface. The laser beams crossed with a small angle above the electrode. The observed fine-structure spectra showed shifts, deformations, and/or splits when varying the distance between the observation position and the electrode surface. The detection limit for the electric field was estimated to be several tens of V/cm.

SESSION TR2: MAGNETRONS II
Thursday Afternoon, 13 October 2016
Room: 2a at 16:00
Jon Gudmundsson, University of Iceland, presiding

Contributed Papers

16:00

TR2 1 Simulation of the electric potential and plasma generation coupling in magnetron sputtering discharges* JAN TRIESCHMANN, DENNIS KRUEGER, FREDERIK SCHMIDT, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Germany* Magnetron sputtering typically operated at low pressures below 1 Pa is a widely applied deposition technique. For both, high power impulse magnetron sputtering (HiPIMS) as well as direct current magnetron sputtering (dcMS) the phenomenon of rotating ionization zones (also referred to as spokes) has been observed. A distinct spatial profile of the electric potential has been associated with the latter [1,2], giving rise to low, mid, and high energy groups of ions observed at the substrate [2]. The adherent question of which mechanism drives this process is still not fully understood. This query is approached using Monte Carlo simulations of the heavy particle (i.e., ions and neutrals) transport consistently coupled to a pre-specified electron density profile via the intrinsic electric field. The coupling between the plasma generation and the electric potential, which establishes correspondingly, is investigated.

While the system is observed to strive towards quasi-neutrality, distinct mechanisms governing the shape of the electric potential profile are identified.

*This work is supported by the German Research Foundation (DFG) in the frame of the transregional collaborative research centre TRR 87.

[1]A. Anders *et al.*, Appl. Phys. Lett. **103**, 144103 (2013).
[2]C. Maszl *et al.*, J. Phys. D: Appl. Phys. **47**, 224002 (2014).

16:15

TR2 2 Global model for active control of capacitive radio frequency magnetron discharges DENNIS ENGEL, DENNIS KRUEGER, CHRISTIAN WOELFEL, MORITZ OBERBERG, JAN LUNZE, PETER AWAKOWICZ, RALF PETER BRINKMANN, *Ruhr University Bochum, Germany* Sputtering technologies have a widespread of applications in modern industries. Up to now, no appropriate model is available for active control of these processes. Controlling inhibits the drift of process parameters and therefore helps to improve the quality of deposited thin films. The aim of this work is to develop a global model for radio frequency capacitively coupled plasma (RF-CCP) magnetron discharges. Several global models for RF-CCPs have been proposed [1], but most of them neglect the existence of a magnetic field inside the plasma. This work builds on existing models but takes into account the underlying magnetic field. Therefore a lumped circuit model with its corresponding system of differential equations is formulated and the influence of the magnetic field is analysed. The proposed model is used to investigate several parameters such as neutral gas pressure, magnetic field strength or applied voltage, to be able to actively control thin film growth.

[1]T. Mussenbrock *et al.*, PSST **16**, 377 (2007).

16:30

TR2 3 Electron dynamics in magnetized technological plasmas: A kinetic description RALF PETER BRINKMANN, DENNIS KRUEGER, *Institute for Theoretical Electrical Engineering, Ruhr-University Bochum* Many advanced thin-film deposition processes like HIPIMS (High Power Impulse Magnetron Sputtering) or PIAD (Plasma-Ion Aided Deposition) employ magnetized plasmas at a pressure range of 0.1 to 1 Pa and a magnetic field of 10 to 100 mT. In such plasmas, the electron gyration radius r_L is of the order of a millimeter, whereas the mean free path λ is much larger, typically comparable with the plasma source dimension L itself (some tens to hundreds of millimeters). It is generally acknowledged that in this regime fluid dynamics fails and a kinetic approach is required. This work employs the smallness of the parameter epsilon $r_L/\lambda \sim r_L/L$ to reduce the complexity of that approach to a tractable level. As an application, the phenomenon of spoke formation in HIPIMS discharges is addressed.

16:45

TR2 4 Modeling of RF Magnetron Plasma in N_2 with dielectric target STEVEN ARBELTIER, *LPGP UMR 8578 CNRS-Université Paris-Sud, Orsay, France / CEA, LETI, Minatec Campus, 17 rue des Martyrs, Grenoble, France* ADRIEN REVEL, *LPGP UMR 8578 CNRS-Université Paris-Sud, Orsay, France* FRÉDÉRIC SABARY, *CEA, Le Ripault, France* CHRISTOPHE SECOUARD, *CEA, LETI, Minatec Campus, 17 rue des Martyrs, Grenoble, France* TIBERIU MINEA, *LPGP UMR 8578 CNRS-Université Paris-Sud, Orsay, France* Thin film batteries technology requires a solid electrolyte suitable for its operation. One option is to use LiPON deposited from Li_3PO_4 target by radio frequency magnetron sputtering in nitrogen plasma. Despite the successful implementation of this technology, the processes occurring into the plasma and at the substrate during deposition need to be well understood. Modelling is an interesting approach to study the undergoing phenomena such as the quantification of plasma species, the potential evolution in the reactor, the shape of the racetrack and the trajectories of sputtered species. The present results are obtained from two models, (i) a 0D model which describes the plasma kinetic and (ii) a 2D model assuming the axial symmetry. The latter uses a Particle-In-Cell Monte-Carlo approach and self-consistently describes the plasma creation and charged particles trajectories in the reactor. The geometry and the magnetic field correspond to a real CEA-LETI reactor .The dielectric target is 6" diameter. Radiofrequency polarization of the target is taken into account in the model. Results on the evolution of ions density in plasma, the electric-field and the self-bias on the target, are discussed.

17:00

TR2 5 Reactive high power impulse magnetron sputtering: combining simulation and experiment TOMAS KOZAK, JAROSLAV VLCEK, *Department of Physics and NTIS - European Centre of Excellence, University of West Bohemia, Univerzitni 8, 306 14 Plzen, Czech Republic* Reactive high-power impulse magnetron sputtering (HiPIMS) has recently been used for preparation of various oxide films with high application potential, such as TiO_2, ZrO_2, Ta_2O_5, HfO_2, VO_2. Using our patented method of pulsed reactive gas flow control with an optimized reactive gas inlet, we achieved significantly higher deposition rates compared to typical continuous dc magnetron depositions. We have developed a time-dependent model of the reactive HiPIMS. The model includes a depth-resolved description of the sputtered target (featuring sputtering, implantation and knock-on implantation processes) and a parametric description of the discharge plasma (dissociation of reactive gas, ionization and return of sputtered atoms and gas rarefaction). The model uses a combination of experimental and simulation data as input. We have calculated the composition of the target and substrate for several deposition conditions. The simulations predict a reduced compound coverage of the target in HiPIMS compared to the continuous dc sputtering regime which explains the increased deposition rate. The simulations show that an increased dissociation of oxygen in a HiPIMS discharge is beneficial to achieve stoichiometric films on the substrate at high deposition rates.

SESSION TR3: HIGH PRESSURE PLASMA CHEMISTRY
Thursday Afternoon, 13 October 2016
Room: 2b at 16:00

Contributed Papers

16:00

TR3 1 Generation and remote delivery of plasma activated species* PAUL MAGUIRE, CHARLES MAHONY, COLIN KELSEY, DAVID RUTHERFORD, DAVIDE MARIOTTI, MANUEL MACIAS-MONTERO, FATIMA PEREZ-MARTIN, *Ulster University* DECLAN DIVER, *Glascow University* Plasma interactions with microdroplets offer new opportunities to deliver active chemical agents and nanoparticles to remote substrates downstream with many potential applications from cancer theranostics and wound healing in biomedicine, gentle food decontamination and seed germination in plasma agriculture to catalyst production and photonic structures fabrication, among others. We demonstrate plasma-liquid based pristine nanomaterials synthesis in flight and subsequent delivery up to 120mm from the atmospheric pressure plasma source. Monosized and non-aggregating metal nanoparticles are formed in the rf plasma in less than 100us, representing an increase in precursor reduction rate that is many (>4) orders of magnitude faster than that observed with standard colloidal chemistry or via high energy radiolytic techniques. Also the collection and purification limitations of the latter are avoided. Plasma activated liquid including OH radicals and H_2O_2 are transported over 120mm and have demonstrated high efficacy bacterial decontamination. These results will be compared with charge species and radical transport from the rf plasma without microdroplets. Reaction models based on high solvated surface electron concentrations will be presented.

*Funding from EPSRC acknowledged (Grants EP/K006088/1 and EP/K006142/1).

16:15

TR3 2 Controlling the nitric and nitrous oxide production of an atmospheric pressure plasma jet CLAIRE DOUAT, *Eindhoven University of Technology, PMP, Eindhoven, The Netherlands / GREMI UMR7344CNRS, University of Orleans, France* SIMON HUBNER, *Research Group Reactive Plasmas, Institute for Experimental Physics II, Ruhr-UniversitÃ¤t Bochum, 44780 Bochum, Germany* RICHARD ENGELN, *Eindhoven University of Technology, PMP, Eindhoven, The Netherlands* JAN BENEDIKT, *Research Group Reactive Plasmas, Institute for Experimental Physics II, Ruhr-UniversitÃ¤t Bochum, 44780 Bochum, Germany* Atmospheric pressure plasma jets are non-thermal plasmas and have the ability to create reactive species. These features make it a very attractive tool for biomedical applications. In this work, we studied NO and N_2O production, which are two species having biomedical properties. NO plays a role in the vascularization and in ulcer treatment, while N_2O is used as anesthetic and analgesic gas. In this study, the plasma source is similar to the COST Reference Microplasma Jet (μ–APPJ). Helium is used as feed gas with small admixtures of molecular nitrogen and oxygen of below 1%. The absolute densities of NO and N_2O were measured in the effluent of an atmospheric pressure RF plasma jet by means of ex-situ quantum-cascade laser absorption spectroscopy via a multi-pass cell in Herriot configuration. We will show that the species' production is dependent on several parameters such as power, flow and oxygen and nitrogen admixture. The NO and N_2O densities are strongly dependent on the N_2-O_2 ratio. Changing this ratio allows for choosing between a NO-rich or a N_2O-rich regime [1].

[1]Douat *et al.*, PSST **25**, 025027 (2016).

16:30

TR3 3 Plasma chemistry in electron-beam sustained discharges MILES TURNER, *Dublin City University* There are many emerging applications that exploit the exotic chemical characteristics of plasmas. Some of these applications, if deployed on an industrial scale, involve processing much larger volumes of gas than seems reasonable using any atmospheric pressure plasma source in wide use today. We note that an electron-beam sustained discharge permits the creation of a atmospheric pressure plasma with reasonable uniformity, large volme, and widely controllable electron temperature. Robust and durable electron beam sources now exist that would facilitate such applications. In this paper we discuss the general advantages of this approach, and we present a modelling study concerned with the production of NO in mixtures of N_2 and O_2, looking towards plasma aided manufacturing of fertilizers.

16:45

TR3 4 Chemistry of neutral species in the effluent of the micro atmospheric pressure plasma jet in water-helium admixture GERT WILLEMS, JAN BENEDIKT, ACHIM VON KEUDELL, *Ruhr-University Bochum* A thorough understanding and good control of produced neutral and charged species by cold atmospheric plasmas is essential for potential environmental and/or bio-medical applications. In this study we use the COST reference micro plasma jet (μ-APPJ), which is a radio-frequency capacitive coupled plasma source with 1 mm electrode distance, which has been operated in helium-water vapour mixture and has been studied as a potential source of hydroxyl radicals and hydrogen peroxide molecules. The water vapour concentration was up to 1.2%. Molecular Beam mass spectrometry is used as diagnostic tool. An absolute calibration of hydrogen peroxide was conducted using a double bubbler concept, because the ionization cross section for hydrogen peroxide is not available. Additionally the effluent chemistry was investigated by use of a 0D and 2D model. Absolute densities of hydrogen peroxide and hydroxyl radicals from atmospheric plasma will be presented. Their dependency on water vapour concentration in the carrier gas as well as distance to target have been investigated. The measured density is between 5E-13 cm-3 (2.4ppm) and 1.5E-14 cm-3 (7.2ppm) for both hydrogen peroxide molecules and hydroxyl radicals. The achieved results are in good agreement with other experiments.

17:00

TR3 5 Reactive species in humidity containing atmospheric pressure plasma jets – Numerical and experimental investigations* SANDRA SCHROETER, J. BREDIN, A. WIJAIKHUM, A. WEST, J. DEDRICK, K. NIEMI, *York Plasma Institute, University of York* A. R. GIBSON, M. FOUCHER, J.-P. BOOTH, *LPP Ecole Polytechnique-CNRS* N. DE OLIVEIRA, D. JOYEUX, L. NAHON, *Synchrotron SOLEIL* Y. GORBANEV, V. CHECHIK, *Dep. of Chemistry, University of York* E. WAGENAARS, T. GANS, D. O'CONNELL, *York Plasma Institute, University of York* The formation and absolute densities of oxygen and hydrogen containing reactive species such as atomic oxygen (O), hydrogen (H), hydroxyl radicals (OH) and hydrogen peroxide (H_2O_2) in an atmospheric pressure plasma jet (APPJ) are investigated as a function of the humidity content in the helium feed gas. APPJs are effective sources for these species, which are known to be biologically active and form a central role in their potential for biomedical applications. To develop and tailor APPJs for therapeutics, quantification of the reactive species produced is necessary. In this work, different diagnostic techniques, such as UV and VUV absorption spectroscopy and picosecond two-photon absorption laser-induced fluorescence (ps-TALIF) and a 0-dimensional chemical kinetics model are applied. We find that the densities of hydrogen containing species increase non-linearly with increasing feed gas humidity. The trend of atomic oxygen depends strongly on impurities present in the APPJ. The model results show that the dominant formation and destruction mechanisms of the species of interest are strongly influenced by the humidity content with different processes dominating at high and low humidity.

*Supported by UK EPSRC (EP/K018388/1, EP/H003797/1), the York-Paris CIRC and LABEX Plas@par (ANR11-IDEX-0004-02).

17:15

TR3 6 Control of ROS and RNS productions in liquid in atmospheric pressure plasma-jet system* GIICHIRO UCHIDA, TAIKI ITO, KOSUKE TAKENAKA, JUNICHIRO IKEDA, YUICHI SETSUHARA, *Osaka University* Non-thermal plasma jets are of current interest in biomedical applications such as wound disinfection and even treatment of cancer tumors. Beneficial therapeutic effects in medical applications are attributed to excited species of oxygen and nitrogen from air. However, to control the production of these species in the plasma jet is difficult because their production is strongly dependent on concentration of nitrogen and oxygen from ambient air into the plasma jet. In this study, we analyze the discharge characteristics and the ROS and RNS productions in liquid in low- and high-frequency plasma-jet systems. Our experiments demonstrated the marked effects of surrounding gas near the plasma jet on ROS and RNS productions in liquid. By controlling the surround gas, the O_2 and N_2 main plasma jets are selectively produced even in open air. We also show that the concentration ratio of NO_2^- to H_2O_2 in liquid is precisely tuned from 0 to 0.18 in deionized water by changing N_2 gas ratio $(N_2/(N_2+O_2))$ in the main discharge gas, where high NO_2^- ratio is obtained at N_2 gas ratio at $N_2/(N_2+O_2) = 0.8$. The low-frequency plasma jet with controlled surrounding gas is an effective plasma source for ROS and RNS productions in liquid, and can be a useful tool for biomedical applications.

*This study was partly supported by a Grant-in-Aid for Scientific Research on Innovative Areas "Plasma Medical Innovation" (24108003) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT).

SESSION TR4: ATMOSPHERIC PLASMA JETS AND SOURCES II

Thursday Afternoon, 13 October 2016
Room: 3 at 16:00

Contributed Papers

16:00

TR4 1 Power dissipated in a non-thermal atmospheric pressure plasma jet measured by miniaturized electrical probes* JUDITH GOLDA, VOLKER SCHULZ-VON DER GATHEN, *Experimental Physics II, Ruhr-Universität Bochum, Universitätsstraße 150, 44780 Bochum, Germany* Non-thermal atmospheric pressure plasma jets are used in bio-medicine, because they generate reactive species at a low gas temperature. Knowledge and control of plasma parameters is required for stable and reliable operation. Therefore, measuring dissipated power in these plasmas is necessary. However, this is challenging because the delivered sender power is often orders of magnitudes higher than the power dissipated in the discharge itself. To measure this dissipated power, we built miniaturized electrical probes directly attached to the jet device [1]. We observed that the dissipated power is a more comprehensive parameter than the common parameter voltage: For example, gas temperature and emission line intensities rose exponentially with increasing voltage but linearly with increasing power. Our analyses further revealed that a substantial proportion of the dissipated power is transformed into heat. In conclusion, miniaturized electrical probes give a fundamental insight into the energy balance of atmospheric pressure plasmas. In the future, these probes can also be adapted to different types of atmospheric pressure plasmas.

*This work was supported by DFG within the frameworks of the Package Project PAK 816.

[1]J. Golda *et al.*, J. Phys. D: Appl. Phys. **49**, 084003 (2016).

16:15

TR4 2 Influence of $Ar/O_2/H_2O$ Feedgas AND $N_2/O_2/H_2O$ Environment on the Interaction of Time Modulated MHz Atmospheric Pressure Plasma Jet (APPJ) with Model Polymers* GOTTLIEB OEHRLEIN, PINGSHAN LUAN, ANDREW KNOLL, *University of Maryland* SANTOSH KONDETI, PETER BRUGGEMAN, *University of Minnesota* An $Ar/O_2/H_2O$ fed time modulated MHz atmospheric pressure plasma jet (APPJ) in a sealed chamber was used to study plasma interaction with model polymers (polystyrene, poly-methyl methacrylate, etc.). The amount of H_2O in the feed gas and/or present in the N_2, O_2, or N_2/O_2 environment was controlled. Short lived species such as O atoms and OH radicals play a crucial role in polymer etching and surface modifications (obtained from X-ray photoelectron spectroscopy of treated polymers without additional atmospheric exposure). Polymer etching depth for Ar/air fed APPJ mirrors the decay of gas phase O atoms with distance from the APPJ nozzle in air and is consistent with the estimated O atom flux at the polymer surface. Furthermore, whereas separate O_2 or H_2O admixture to Ar enhances polymer etching, simultaneous addition of O_2 and H_2O to Ar quenches polymer etching. This can be explained by the mutual quenching of O with OH, H and HO_2 in the gas phase. Results where O_2 and/or H_2O in the environment were varied are consistent with these mechanisms. All results will be compared with measured and simulated species densities reported in the literature.

*We gratefully acknowledge funding from US Department of Energy (DE-SC0001939) and National Science Foundation (PHY-1415353).

16:30

TR4 3 Electrode Configurations in Atmospheric Pressure Plasma Jets* AMANDA M. LIETZ, MARK J. KUSHNER, *University of Michigan* Atmospheric pressure plasma jets (APPJs) are being studied for emerging medical applications including cancer treatment and wound healing. APPJs typically consist of a dielectric tube through which a rare gas flows, sometimes with an O_2 or H_2O impurity. In this paper, we present results from a computational study of APPJs using *nonPDPSIM*, a 2-D plasma hydrodynamics model, with the goal of providing insights on how the placement of electrodes can influence the production of reactive species. Gas consisting of $He/O_2 = 99.5/0.5$ is flowed through a capillary tube at 2 slpm into humid air, and a pulsed DC voltage is applied. An APPJ with two external ring electrodes will be compared with one having a powered electrode inside and a ground electrode on the outside. The consequences on ionization wave propagation and the production of reactive oxygen and nitrogen species (RONS) will be discussed. Changing the electrode configuration can concentrate the power deposition in volumes having different gas composition, resulting in different RONS production. An internal electrode can result in increased production of NO_x and HNO_x by increasing propagation of the ionization wave through the He dominated plume to outside of the tube where humid air is diffusing into the plume.

*Work supported by US DOE Office of Fusion Energy Science and the National Science Foundation.

16:45

TR4 4 Numerical and experimental study on the dynamics of a μs helium plasma gun with various amounts of O_2 admixture* PEDRO VIEGAS, *LPP, Ecole Polytechnique, France* XAVIER DAMANY, SYLVAIN ISENI, JEAN-MICHEL POUVESLE, ERIC ROBERT, *GREMI, Orleans, France* ANNE BOURDON, *LPP, Ecole Polytechnique, France* The use of admixtures (mostly O_2 and N_2) to a helium buffer has been studied recently to tailor the generation of reactive species in plasma jets for biomedical applications. So far, most experiments have been dedicated to the study of the plasma plume. For endoscopic treatments, it is also important to better understand and optimize the propagation of discharges in long dielectric tubes as catheters. In this work, we present an experimental and numerical study on the dynamics of a μs helium plasma discharge with O_2 admixture in a long dielectric tube. In simulations, a 2D fluid model is used. For comparison purposes, the geometries of the set-ups used for simulations and experiments are as close as possible. We compare experiments and simulations for different amounts of O_2 admixture added to the buffer gas and present results on the velocity of the discharge front for the various amounts of O_2 and different applied voltages. In order to study the influence of different amounts of O_2 admixture on the helium discharge dynamics, detailed kinetic schemes have been used. The influence of Penning and charge exchange reactions on the discharge structure and dynamics are studied, as well as the role of negative ions.

*P.V. is supported by an EDOM fellowship, and X.D. by an INEL/Region Centre-Val de Loire fellowship.

17:00

TR4 5 Atomic oxygen behavior at downstream of AC excited atmospheric pressure He plasma jet KEIGO TAKEDA, KENJI ISHIKAWA, HIROMASA TANAKA, MAKOTO SEKINE, MASARU HORI, *Nagoya Univ.* Applications of atmospheric pressure plasma jets (APPJ) have been investigated in the plasma medical fields such as cancer therapy, blood coagulation, etc. Reactive species generated by the plasma jet interacts with the biological surface. Therefore, the issue attracts much attentions to investigate the plasma effects on targets. In our group, a spot-size AC excited He APPJ have been used for the plasma medicine. From diagnostics of the APPJ using optical emission spectroscopy, the gas temperature and the electron density was estimated to be 299 K and 3.4×10^{15} cm^{-3}. The AC excited He APPJ which affords high density plasma at room temperature is considered to be a powerful tool for the medical applications. In this study, by using vacuum ultraviolet absorption spectroscopy, the density of atomic oxygen on a floating copper as a target irradiated by the He APPJ was measured as a function of the distance between the plasma source and the copper wire. The measured density became a maximum value around 8×10^{13} cm^{-3} at 12 mm distance, and then decreased over the distance. It is considered that the behavior was due to the changes in the plasma density on the copper wire and influence of ambient air.

17:15

TR4 6 Photochemical/Microchannel Plasma Reactors Driven By High Power Vacuum Ultraviolet Lamps CHUL SHIN, SUNG-JIN PARK, GARY EDEN, *University of Illinois, Department of Electrical and Computer Engineering* Experiments are being conducted in which molecular dissociation or other chemical reactions in microchannel plasmas are accelerated by the introduction of vacuum ultraviolet photons. Initial emphasis is being placed on recently-developed Xe_2 lamps that are efficient sources of 172 nm ($h\nu \approx$ 7.2 eV) photons. Thin, flat lamps, fabricated from fused silica and having microcavity arrays internal to the lamp, have been developed by the University of Illinois and Eden Park Illumination and produce intensities above 200 mW/cm^2. Integrating such lamps into a microcavity plasma reactor yields a hybrid photochemical/plasma system in which product yield and power consumption can be optimized. The selectivity of photodissociation in generating radicals and atomic fragments offers new synergies in plasma processing. Data concerning CO_2 dissociation in arrays of microchannel plasmas, and the modification of this process by external 172 nm radiation, will be presented.

SESSION TR6: RECEPTION AND BANQUET

Thursday Evening, 13 October 2016; Room: Henrichs Gebläsehalle, Hattingen at 18:00;

SESSION UF1: ELECTRON-IMPACT COLLISIONS
Friday Morning, 14 October 2016; Room: 1 at 8:30; Bruno de Harak, Illinois Wesleyan University, presiding

Invited Papers

8:30

UF1 1 Electron Impact Ionization and Fragmentation Dynamics of Small Atomic and Molecular Clusters
ALEXANDER DORN, *Max Planck Institute for Nuclear Physics*

New ionization and fragmentation reactions emerge if target atoms or molecules are embedded in an environment as it is the case in small clusters or in the condensed phase. These can be intermolecular energy and charge transfer processes or a completely modified fragmentation behavior of the molecular ions. Here we study low energy electron impact induced ionization with a multi-electron and ion imaging spectrometer (reaction microscope) and a supersonic gas jet target which can produce small clusters of various target species. Interatomic reactions are studied for the model system of weakly bound Ar_2 dimers. Here, the coincident detection of three electrons and two ions gives detailed insight in interatomic Coulombic decay and radiative charge transfer processes. Such processes were also found in bio-relevant systems like water clusters. We studied pure and water-mixed clusters of tetrahydrofuran (C_4H_8O, THF) which is the simplest analog of deoxyribose in the DNA backbone. One observation is that ionization of the outermost valence orbital for the monomer leads to stable THF ions. In contrast if THF is bound to another THF or a water molecule the molecular ring breaks. In addition we identify intermolecular Coulombic decay induced by energy transfer from a water molecule ionized in the inner valence shell to the neighboring THF molecule.

Contributed Papers

9:00

UF1 2 Inner shell excitation of Cu, Ag and Au ALLAN STAUFFER, *York University* ROBERT MCEACHRAN, *Australian National University* The ground states of Cu, Ag and Au have the configuration $nd^{10}(n+1)s$ with $n = 3$, 4 and 5. The lowest excited manifold for Cu and Au has the configuration $nd^9(n+1)s^2$ which is well separated from the next excited manifold $nd^{10}(n+1)p$. However, for Ag, the lowest $4d^95s^2$ level with $J = 5/2$ lies between the two levels of the $4d^{10}5p$ manifold. In [1] we compared our Relativistic Distorted Wave calculations for the excitation of the $4d^{10}5p$ manifold with experimental measurements which would have included a contribution from the $4d^95s^2$ $J = 5/2$ level. While we do not expect the cross section for this forbidden transition to be large compared to the optical allowed transitions of the P levels, we decided to investigate excitation of these inner shell levels, in part because they are the lowest excited levels in Cu and Au, We will discuss the theoretical expressions for these excitations as well as give numerical results of our cross section calculations.

[1]S. D. Tošić, V. Pejčev, D. Šević, R. P. McEachran, A. D. Stauffer, and B. P. Marinković, Phys. Rev. A **91**, 052703 (2015).

9:15

UF1 3 Differential cross sections for atomic ionization determined through the Bohm's velocity field JUAN M RANDAZZO, *Centro Atomico Bariloche, Argentina* LORENZO UGO ANCARANI, *Universite de Lorraine, France* FLAVIO D COLAVECCHIA, *Centro Atomico Bariloche, Argentina* Differential cross sections for atomic ionization are usually evaluated via the scattering amplitude defined as the transition matrix element between the initial and final states of the collision. R. Peterkop proposed an alternative approach – known as flux formula - based on the relation linking the cross section to the ratio between the incident electronic flux and the emitted post-collisional one, through the asymptotic outgoing behavior of the scattering wave function. The flux formula was seen to fail for very unequal energy sharing when evaluating Single Differential Cross Sections (SDCSs) for the s-wave electron-hydrogen problem [1]. The procedure was thereafter abandoned. However, an alternative way of defining the electrons' local momenta by using the Bohm's velocity field was recently proposed [2], and it was found that SDCS results with a new definition of the energy fraction are well behaved on the whole range. In this contribution, we apply the modified quantum flux approach with local momenta to the electron impact ionization of hydrogen by considering the problem in its whole dimensionality, i.e., not only the s-wave contribution. We compare triple differential cross section results with other theoretical and experimental data, and this for several incident energies.

[1]M. Baertschy *et al.*, Phys. Rev. A **60**, R13 (1999).
[2]J. M. Randazzo and L. U. Ancarani, Phys. Rev. A **82**, 062706 (2015).

Invited Papers

9:30

UF1 4 R-matrix calculations in support of impurity influx measurements
C. P. BALLANCE, *CTAMOP, Queen's University of Belfast, Belfast, Northern Ireland*

The RMPS (R-Matrix with Pseudo-States) method has been used with great success in the calculation of the collisional data for light fusion-related elements such as helium, beryllium or neon, both in terms of electron-impact excitation and also ground, metastable, and excited state ionisation. However, more complex atomic species such as Molybdenum and Tungsten have been choosen as plasma-facing elements in several tokamak experiments such as NSTX-U†. During plasma operation there is an inevitable degree of wall erosion and therefore the determination of this impurity-influx rate from vessel walls needs to be characterized. In terms of atomic physics, this erosion rate can be determined from an SXB ratio and spectroscopic measurements of emitted line radiation. The SXB ratio is generated using a combination of electron-impact ionisation, excitation and the underlying atomic structure transition probabilities. The groundstate of Mo I and Mo II being half-open d shell systems quickly give rise to 100s of levels, and therefore the resulting spectral lines from the neutral and singly ionised species provides a convoluted picture. Therefore, subject to the constraints of spectrometer used, theoretically we are able to survey our structure and collisional calculations and pro-actively suggest particular diagnostic lines. There have been previous R-matrix calculations in LS coupling used for modelling of Mo, with mixed results, however it is hoped that this project shall resolve those differences. A method shall be presented that we use to determine which lines are most beneficial for analysis. I will present current electron-impact excitation and ionisation results for both neutral and singly ionised molybdenum.

[1]Plasma Phys. Control. Fusion **55**, 125010 (2013).

Contributed Papers

10:00

UF1 5 Benchmark calculations for electron-impact excitation and ionization of beryllium* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* DMITRY V. FURSA, IGOR BRAY, *Curtin University* The *B*-spline *R*-matrix [1] and the convergent close-coupling methods [2] are used to study electron collisions with neutral beryllium for energies from threshold to 100 eV. Coupling to the target continuum significantly affects the results for transitions from the ground state, but to a lesser extent the strong transitions between excited states. Cross sections are presented for selected transitions between low-lying physical bound states of beryllium, as well as for elastic scattering, momentum transfer, and ionization. The present cross sections for transitions from the ground state from the two methods are in excellent agreement with each other, and also with previous results based on nonperturbative convergent pseudostate and time-dependent close-coupling models. The elastic cross section at low energies is dominated by a shape resonance. The ionization from the $(2s2p)^3P$ and $(2s2p)^1P$ states strongly depends on the respective term. The current predictions represent an extensive set of electron scattering data for neutral beryllium, which should be sufficient for most modeling applications.

*This work was supported by the United States National Science Foundation (OZ and KB) and the Australian Research Council (DVF and IB).

[1]O. Zatsarinny and K. Bartschat, J. Phys. B **46**, 112001 (2013).
[2]I. Bray *et al.*, Phys. Rep. **520**, 135 (2012).

10:15

UF1 6 Ionization Cross Sections for Electron Collision from PCl_5 SATYENDRA PAL, *MMH College, Ghaziabad (UP)* Phosphorous pentachloride PCl_5 and its free radicals are widely used in plasma, plasma-assisted etching and deposition of phosphorous layers in the fabrication of microelectronic components and other high technological devices. Keeping the wide interest of the molecule, in the present work, we report the calculations for differential cross sections as a function of secondary and or ejected electron energy in the ionization of PCl_5 by electron collision corresponding into the production of various cations singly charged ions through direct and dissociative ionization processes at a fixed incident electron energy of 100 eV. The modified Jain-Khare semi-empirical formalism [1-2] based on oscillator strength has been employed for evaluation of cross sections. The corresponding derived partial integral cross sections in terms of the partial ionization cross sections for these cations in the energy range varying from ionization threshold to 1000 eV, revealed a reasonably good agreement with the available data. In addition to the differential and integral ionization cross sections, we have also calculated the ionization rate coefficients using the evaluated partial ionization cross sections and the Maxwell-Boltzmann distribution as a function of electron energy.

SESSION UF2: CHEMICAL MODELING
Friday Morning, 14 October 2016; Room: 2a at 8:30; Miles Turner, National Center for Plasma Science Technology Ireland, presiding

Invited Papers

8:30

UF2 1 Modeling Complex Chemical Systems: Problems and Solutions
JAN VAN DIJK, *Eindhoven University of Technology*

Non-equilibrium plasmas in complex gas mixtures are at the heart of numerous contemporary technologies. They typically contain dozens to hundreds of species, involved in hundreds to thousands of reactions. Chemists and physicists have always been interested in what are now called *chemical reduction techniques* (CRT's). The idea of such CRT's is that they reduce the number of species that need to be considered *explicitly* without compromising the validity of the model. This is usually achieved on the basis of an analysis of the reaction time scales of the system under study, which identifies species that are in *partial equilibrium* after a given time span. The first such CRT that has been widely used in plasma physics was developed in the 1960's and resulted in the concept of *effective* ionization and recombination rates [1]. It was later generalized to systems in which multiple levels are effected by transport [2]. In recent years there has been a renewed interest in tools for chemical reduction and reaction pathway analysis. An example of the latter is the PumpKin tool [3]. Another trend is that techniques that have previously been developed in other fields of science are adapted as to be able to handle the plasma state of matter. Examples are the Intrinsic Low Dimension Manifold (ILDM) method and its derivatives, which originate from combustion engineering, and the general-purpose Principle Component Analysis (PCA) technique [4]. In this contribution we will provide an overview of the most common reduction techniques, then critically assess the pros and cons of the methods that have gained most popularity in recent years. Examples will be provided for plasmas in argon and carbon dioxide.

[1]D. R. Bates, A. E. Kingston, and R. W. P. McWhirter, Proc. R. Soc. A **267**, 297 (1962).
[2]J. van Dijk, A. Hartgers, J. Jonkers, and J. A. M. van der Mullen, J. Phys. D **33**, 2798 (2000).
[3]A. H. Markosyan, A. Luque, F. J. Gordillo-Vázquez, and U. Ebert, Comp. Phys. Comm. **185**, 2697 (2014). The underlying algorithm is discussed in: Ralph Lehmann, J. Atmos. Chem. **47**, 45 (2004).
[4]K. S. C. Peerenboom, A. Parente, T. Kozak, A. Bogaerts, and G. Degrez, Plasma Sources Science and Technology **24**, 025004 (2015).

Contributed Papers

9:00

UF2 2 A study on ultraviolet photochemical effects on low-pressure oxygen plasmas SIJUN KIM, JANGJAE LEE, KWANGKI KIM, YOUNGSUK LEE, DAEWOON KIM, SHIN-JAE YOU,* *Chungnam National University* Low pressure oxygen plasmas have been applied to various industrial processing such as cleaning, ashing and oxidation. Many studies have investigated characteristics of oxygen plasma through plasma modeling and experiments. Although oxygen plasmas are electronegative discharges, photochemical effects on negative ion species and neutral radicals have not yet fully understood. In this study we use a global model (volume averaged) in capacitive reactor design to understand ultraviolet photochemical effect on low-pressure oxygen plasmas and compare with experiments.

*corresponding author.

9:15

UF2 3 Level-lumping method for the modeling of CO_2 vibrational kinetics* ANTONIN BERTHELOT, ANNEMIE BOGAERTS, *University of Antwerp, Plasmant* UNIVERSITY OF ANTWERP, PLASMANT TEAM The conversion of greenhouse gases, especially CO_2, into value-added chemicals is gaining a very large interest among the scientific and industrial communities. It is known that the excitation of the asymmetric vibrational mode of CO_2 is one of the most important processes to achieve high energy efficiencies, thus making the CO_2 kinetics very complex. Due to this complexity, the only models that have been developed so far were zero-dimensional models, considering only the variations over time. These models require strong approximations on the geometry of the reactor. In order to reduce the calculation time and to allow the modeling of complex plasma problems in 2D or 3D geometries, we have simplified the chemistry set of CO_2 and developed a lumped-levels model for the vibrational kinetics. It was found that a 3-groups model gives a good agreement with the state-to-state model at pressures of 100mbar and above, at the conditions under study. The important dissociation and recombination mechanisms of CO_2 have also been investigated. This lumped-levels model is being implemented in a 2D self-consistent microwave plasma code.

*This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under Grant Agreement No. 606889.

9:30

UF2 4 The kinetics of energetic O^- ions in oxygen discharge plasmas* ALEXANDER PONOMAREV, *SSC Keldysh Research Center* NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* SSC KELDYSH RESEARCH CENTER TEAM, MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY TEAM Monte Carlo simulation was used to study the translational relaxation of energetic O^- ions formed due to dissociative electron attachment to O_2 molecules in oxygen and oxygen-containing mixtures in a strong electric field. Initial O^- ions have rather high energies and are more reactive then the ions reaching equilibrium with electric field. Therefore, there is a noticeable probability that electron detachment from the energetic O^- ions or their charge transfer to form O_2^- ions proceed prior to energy degradation of these ions. The probabilities of electron detachment and charge transfer were calculated as a function of the reduced electric field in oxygen and some oxygen-containing mixtures. Comparison with available information about the electron detachment and charge transfer rate coefficients for O^- ions shows that the effect of high reactivity of the initial energetic ions can lead to orders of magnitude increase in the effective rates of these reactions and should be considered in numerical simulation of the properties of discharge plasmas in oxygen and oxygen-containing mixtures.

*This work was partially supported by the Russian Foundation of Basic Research under the Project No. 16-32-00196.

9:45

UF2 5 A validation study on CO_2 chemistry PETER KOELMAN, *Eindhoven University of Technology* STIJN HEIJKERS, *Antwerp University* SAMANEH TADAYON MUSAVI, *Eindhoven University of Technology* WOUTER GRAEF, *Plasma Matters* ANNEMIE BOGAERTS, *Antwerp University* JAN DIJK, VAN, *Eindhoven University of Technology* ELEMENTARY PROCESSES IN GAS DISCHARGES TEAM, PLASMANT TEAM The demand for renewable energy has increased the popularity of various energy sources, such as solar and wind energy. These sources are intermittent by nature, which typically does not match the demand of energy. Therefore, storage of energy is needed. Current tools for this are, however, costly, slow, and inefficient. Storing energy by the formation of valuable fuels from CO_2 is potentially an improvement. By plasma assisted CO_2 dissociation CO is produced. In subsequent steps the CO is transformed in valuable fuels. An extensive CO_2 microwave plasma chemistry is studied, with special attention to the vibrational modes, which provide a pathway for the dissociation. To that end we developed a global model, which is only time resolved and needs less computational time than spatially resolved models. We present the results from a verification study of the CO_2 chemistry. This is done by verification of input data, and by comparison of results obtained by two independent models: ZDPlaskin and PLASIMO's Global Model. We also present results from a sensitivity study of the input data.

Invited Papers

10:00

UF2 6 Selfconsistent vibrational and free electron kinetics for CO_2 dissociation in cold plasmas

MARIO CAPITELLI, *CNR NANOTEC_Plasmi Lab (Bari, Italy)*

The activation of CO_2 by cold plasmas is receiving new theoretical interest thanks to two European groups [1-2]. The Bogaerts group developed a global model for the activation of CO_2 trying to reproduce the experimental values for DBD and microwave discharges. The approach of Pietanza et al was devoted to understand the dependence of electron energy distribution function (eedf) of pure CO_2 on the presence of concentrations of electronically and vibrationally excited states taken as parameter. To understand the importance of the vibrational excitation in the dissociation process Pietanza et al compared an upper limit to the dissociation process from a pure vibrational mechanism (PVM) with the corresponding electron impact dissociation rate, the prevalence of the two models depending on the reduced electric field and on the choice of the electron molecule cross section database [2]. Improvement of the Pietanza et al model is being considered [3] by coupling the time dependent Boltzmann solver with the non equilibrium vibrational kinetics of asymmetric mode and with simplified plasma chemistry kinetics describing the ionization/recombination process and the excitation-deexcitation of a metastable level at 10.5eV. A new PVM mechanism is also considered. Preliminary results [3], for both discharge and post discharge conditions, emphasize the action of superelastic collisions involving both vibrationally and electronically excited states in affecting the eedf. The new results can be used to plan a road map for future developments of numerical codes for rationalizing existing experimental values, as well as, for indicating new experimental situations.

[1]T. Kozak and A. Bogaerts, Plasma Sources Sci. Technol. **24**, 042002 (2015).
[2]L. D. Pietanza, G. Colonna, G. D'Ammando, A. Laricchiuta, and M. Capitelli, Plasma Sources Sci. Technol. (Fast Track Communication) **24**, 042002 (2015); J. Phys. Chem. A **120**, 2614 (2016).
[3]L. D. Pietanza *et al.*, Plasma Phys. Control. Fusion (2016) submitted.

SESSION UF3: THERMAL PLASMAS

Friday Morning, 14 October 2016
Room: 2b at 8:30
Pierre Tardiveau, University of Paris, presiding

Contributed Papers

8:30

UF3 1 Unstable Behavior of Anodic Arc Discharge for Synthesis of Nanomaterials* SOPHIA GERSHMAN, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* Fast imaging and electrical current measurements reveal unstable behavior of the carbon arc discharge for synthesis of nanomaterials. The arc column and the arc attachment region to the anode move in a somewhat sporadic way with a characteristic time in a 10^{-3} sec range. The arc exhibits a negative differential resistance before the arc motion occurs. A physical mechanism is proposed based on the thermal processes in the arc plasma region interacting with the ablating anode which leads to the shift of the arc to a new anode region. According to the transient heat transfer analysis, the time needed to heat a new anode region is also in a 10^{-3} sec range. For a 0.6 cm diameter anode used in our experiments, this time yields a frequency of about 200-300 Hz, comparable to the measured frequency of the arc motion. The voltage and current measurements show oscillations with a similar characteristic frequency. The thermal model is indirectly supported by the measured negative differential resistance of the arc discharge during arc oscillations. The observed unstable behavior of the arc may be responsible for the mixing of the flow of nanoparticles during the synthesis of nanoparticles leading to poor selectivity typical for the arc synthesis.

*The work was supported by US DOE under Contract No. DE-AC02-09CH11466.

8:45

UF3 2 Coagulation of carbon nanoparticles in the acoustic field in the vicinity of the arc discharge* MIKHAIL SHNEIDER, *Princeton University* An arc discharge produced in a background inert gase between graphite electrodes is one of the popular methods of nanoparticle synthesis. Nanoparticles and microscopic soot particles are produced in the peripheral region of arc. Intensive soot generation significantly reduces the efficiency of the arc as the technological process for production of fullerenes and other nanoparticles. Experimental studies have shown that exposure of peripheral region of the arc to intense ultrasound leads to a noticeable increase in the efficiency of the nanoparticle synthesis and reduces the soot yield (see, e.g. [1]), because ultrasound causes coagulation of soot particles and decrease of their concentration without affecting the nanoparticles. The paper presents theoretical study of the threshold for the ultrasound intensity required for the coagulation as a function of particle sizes and charge, and background gas parameters. The charge acquired in a thermionic emission, as a result of particles heating by radiation from the arc, is calculated self-consistently [2,3]. I would like to thank Dr. Yevgeny Raitses, Dr. Igor Kaganovich, and Mr. James Mitrani for their interest in this work and fruitful discussions.

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

[1]G. N. Churilov, Nanotubes and Carbon Nanostructures **16**, 395 (2008).
[2]M. N. Shneider, Phys. Plasmas **22**, 073303 (2015),
[3]M. N. Shneider, AIAA 2016-1693, 54th AIAA Aerospace Sciences Meeting, San Diego, CA, 2016.

9:00

UF3 3 Fluid simulation of carbon arc plasma* KENTARO HARA, YEVGENY RAITSES, IGOR KAGANOVICH, *Princeton Plasma Phys Lab* An arc discharge using graphite electrodes is known to produce carbon nanomaterials, e.g. nanotubes and fullerenes. In order to understand where and how such nanomaterials are synthesized, the plasma properties inside the arc discharge must be characterized. The mechanism of the carbon arc plasma is as follows. Carbon particles evaporate from the graphite anode, which is mainly heated by the electrons. Carbon atoms and ions condensate and form a deposit on the cathode, from which the electrons are thermionically emitted. A one-dimensional fluid model is developed to study the characteristics of the carbon arc plasma in atmospheric pressures. Sheath models for the anode and cathode are coupled to the fluid simulation to obtain the material temperature and sheath potential. In the model, thermal nonequilibrium is assumed and atomic carbon, dimer, and trimer are considered. A typical operating condition of a carbon arc plasma is discharge voltage of 20 V, discharge current of 60 A, the electron radius of 6 to 12 mm, and background pressure of 500 Torr. Transition from low to high ablation mode is obtained from the simulations with a smaller electrode radius and with a larger discharge current, which agrees with experimental observations.

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

9:15

UF3 4 Two color interferometric electron density measurement in an axially blown arc PATRICK STOLLER, JAN CARSTENSEN, BERNARDO GALLETTI, CHARLES DOIRON, ALEXEY SOKOLOV, RENÉ SALZMANN, SANDOR SIMON, PHILIPP JABS, *ABB Switzerland Ltd.* High voltage circuit breakers protect the power grid by interrupting the current in case of a short circuit. To do so an arc is ignited between two contacts as they separate; transonic gas flow is used to cool and ultimately extinguish the arc at a current-zero crossing of the alternating current. A detailed understanding of the arc interruption process is needed to improve circuit breaker design. The conductivity of the partially ionized gas remaining after the current-zero crossing, a key parameter in determining whether the arc will be interrupted or not, is a function of the electron density. The electron density, in turn, is a function of the detailed dynamics of the arc cooling process, which does not necessarily occur under local thermodynamic equilibrium (LTE) conditions. In this work, we measure the spatially resolved line-integrated index of refraction in a near-current-zero arc stabilized in an axial flow of synthetic air with two nanosecond pulsed lasers at wavelengths of 532 nm and 671 nm. Generating a stable, cylindrically symmetric arc enables us to determine the three-dimensional index of refraction distribution using Abel inversion. Due to the wavelength dependence of the component of the index of refraction related to the free electrons, the information at two different wavelengths can be used to determine the electron density. This information allows us to determine how important it is to take into account non-equilibrium effects for accurate modeling of the physics of decaying arcs.

9:30

UF3 5 Electrical characteristics of TIG arcs in argon from non-equilibrium modelling and experiment MARGARITA BAEVA, DIRK UHRLANDT, *Leibniz Institute for Plasma Science and Technology INP Greifswald e.V., Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* ERWAN SIEWERT, *Linde AG, Geschäftsbereich Linde Gas, Carl-von-Linde-Str. 25, 85716 Unterschleissheim, Germany* Electric arcs are widely used in industrial processes so that a thorough understanding of the arc characteristics is highly important to industrial research and development. TIG welding arcs operated with pointed electrodes made of tungsten, doped with cerium oxide, have been studied in order to analyze in detail the electric field and the arc voltage. Newly developed non-equilibrium model of the arc is based on a complete diffusion treatment of particle fluxes, a generalized form of Ohm's law, and boundary conditions accounting for the space-charge sheaths within the magneto-hydrodynamic approach. Experiments have been carried out for electric currents in the range 5-200 A. The electric arc has been initiated between a WC20 cathode and a water-cooled copper plate placed 0.8 mm from each other. The arc length has been continuously increased by 0.1 mm up to 15 mm and the arc voltage has been simultaneously recorded. Modelling and experimental results will be presented and discussed.

9:45

UF3 6 Course of organized structures in thermal plasma inside and outside argon plasma torch* JAN GRUBER, JIRI SONSKY, JAN HLINA, *Institute of Thermomechanics AS CR, v.v.i., Academy of Sciences of the Czech Republic, Dolejskova 5, 182 00 Praha 8, Czech Republic* Arc chamber of direct-current (dc) argon plasma torch and area just above the nozzle outside of this dc plasma torch were observed by hi-speed camera. System of reflecting mirrors and transparent silica arc chamber walls were used to obtain simultaneous records of both i) cathode area with electric arc inside the plasma torch and ii) nozzle exit with resulting plasma jet outside the plasma torch. Such experimental arrangement allowed us to track localized repeating patterns (organized structures) in the arc chamber and in the plasma flow. Identification of various organized structures - for different experimental conditions - according to their origin and typical development is presented in this paper. Impact of 300 Hz ripple in arc current was compared between different areas of the plasma. Additional simultaneous observation of plasma flow in the same system by series of photodiodes was used for verification of the results.

*The work was possible with institutional support RVO:61388998.

10:00

UF3 7 Synthesis of boron-nitride nanocages and fullerenes in a BN plasma* PREDRAG KRSTIC, LONGTAO HAN, *State Univ of NY- Stony Brook* Synthesis of boron-nitride fullerenes, nanococoons and nano-cages by self-organization of BN molecules in a high-temperature plasma is simulated using the DFT tight-binding method. No boron nano-cluster or catalysts nano-particle are needed to initiate this process. By varying the plasma temperature and the BN density, as well as the time of growth we can simulate growth of he sp^2 cages of various shape, size and quality. Role of hydrogen in HBNH and H_2BNH_2 synthesis is also considered,

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

10:15

UF3 8 Plasma-produced nanocrystals enable new insights in semiconductor physics* BENJAMIN GREENBERG, ZACHARY ROBINSON, CLAUDIA GORYNSKI, BRYAN VOIGT, LORRAINE FRANCIS, ERAY AYDIL, UWE KORTSHAGEN, *University of Minnesota* The transition from semiconducting (insulating) to metallic behavior is a central problem of semiconductor physics. In bulk semiconductors, this insulator-to-metal transition is described by the well-known Mott criterion. However, in films of semiconductor nanocrystals the Mott criterion fails completely. Recent progress in the nonthermal plasma synthesis of films of highly doped silicon nanocrystals has contributed to the development of a new theory that presents a consistent analog to the Mott criterion for nanocrystal materials [1]. Here, we study films of nonthermal plasma produced zinc oxide (ZnO) nanocrystals to in detail investigate the insulator-to-metal transition. We produce high-purity monodisperse ZnO nanocrystals in a nonthermal plasma and form dense films via supersonic impact deposition. We then modulate the free carrier density, n, and nanocrystal contact facet radius, ρ, via xenon-flashlamp intense pulsed light annealing, which induces necking between the clean surfaces of adjacent nanocrystals. Preliminary electrical measurements indicate that the electron mobility can be finely tuned and that the films cross the insulator-to-metal transition for sufficiently high n and ρ.

*This work was supported by the MRSEC program of the U.S. National Science Foundation under grant DMR-1420013.

[1]T. Chen *et al.*, Nat. Mater. **15**, 299 (2016).

SESSION VF1: ELECTRON COLLISIONS WITH SMALL MOLECULES

Friday Morning, 14 October 2016; Room: 1 at 11:00; Zoran Petrovic, University of Belgrade, presiding

Invited Papers

11:00

VF1 1 Electronic excitation of molecular hydrogen by low-energy electrons

LEIGH HARGREAVES, *California State University Fullerton*

Molecular hydrogen is the most abundant element in the universe, particularly in interstellar plasmas such as atmospheres of gas giant planets and stars. Electron collision data for hydrogen is critical to interpreting the spectroscopy of interstellar objects, as well as being of applied value for modelling technological plasmas. Hydrogen is also fundamentally interesting, as while highly accurate wave functions for this simple molecule are available, providing an accurate, ab initio, treatment the collision dynamics has proven challenging, on account of the need to have a complete description of channel coupling and polarization effects. To date, no single theoretical approach has been able to replicate experimental results across all transitions and incident energies, while the experimental database that is available is far from complete and not all available measurements are in satisfactory agreement. In this talk, we present differential and integral cross section measurements for electronic excitation cross sections for molecular hydrogen by low-energy electron impact. The data were measured at incident energies below 20eV, using a well-tested crossed beam apparatus and employing a moveable gas source approach to ensure that background contributions to the scattering are accurately accounted for. These measurements are compared with new theoretical results employing the convergent close coupling approach.

Contributed Papers

11:30

VF1 2 CCC calculated integrated cross sections of electron-H_2 scattering* MARK ZAMMIT, *Theoretical Division, Los Alamos National Laboratory* DMITRY FURSA, JEREMY SAVAGE, IGOR BRAY, *Curtin University* Recently we applied the molecular convergent close-coupling (CCC) method to electron scattering from molecular hydrogen H_2 [1]. Convergence of the major integrated cross sections has been explicitly demonstrated in the fixed-nuclei approximation by increasing the number of H_2 target states in the close-coupling expansion from 9 to 491. The calculations have been performed using a projectile partial wave expansion with maximum orbital angular momentum $L_{max} = 8$ and total orbital angular momentum projections $|M| \leqslant 8$. Coupling to the ionization continuum is modeled via a large pseudo state expansion, which we found is required to obtain reliable elastic and excitation cross sections. Here we present benchmark elastic, single-ionization, electronic excitation and total integrated cross sections over a broad energy range (0.1 to 300 eV) and compare with available experiment and previous calculations.

*Los Alamos National Laboratory and Curtin University.

[1]M. C. Zammit *et al.*, Phys. Rev. Lett. **116**, 233201 (2016).

Invited Papers

11:45

VF1 3 Theoretical studies on dissociative recombination of molecular ions

ÅSA LARSON, *Department of Physics, Stockholm University*

In dissociative recombination a molecular ion captures an electron forming a neutral state that dissociates into fragment. Due to the Coulomb attraction between the reactants, the cross section is typically large at low collision energies and the process is important for different types of plasmas. Here, it will be described how the reaction can be studied theoretically. The goal is to compute reaction cross sections and to determine what fragments are formed. The calculations are done in close collaboration with experiments. In the process, the electron may be captured directly into an electronic resonant state that then is dissociated into fragments. An alternative mechanism is driven by an electron capture into a ro-vibrationally excited Rydberg state that then is predissociated. The two mechanisms are competing and should be considered coherently. The study of dissociative recombination requires both the accurate treatment of the electron scattering processes, but must also include an accurate representation of the potential energy curves, both for electronically bound states and the resonant states. In addition, the couplings between these states, both the coupling between the resonant states and the scattering continuum (the autoionization width) and the non-adiabatic coupling between all states are needed to complete describe the cross section including the branching ratios into final states. These are obtained using structure calculations as well as scattering calculations, using the complex Kohn variational method. The electronic states are diabatized before the nuclear dynamics is studied quantum mechanically. The theoretical method will be illustrated with examples on dissociative recombination of small molecular ions such as HF^+, BeH^+, H_2O^+ and N_2H^+.

Contributed Papers

12:15

VF1 4 Vibrational excitation in $O_2$and Cl_2inductively-coupled plasmas and DC discharges* JEAN-PAUL BOOTH, DANIL MARINOV, MICKAEL FOUCHER, *LPP, CNRS-Ecole Polytechnique-UPMC* ADRIANA ANNUSOVA, *Comenius University, Bratislava, Slovakia* VASCO GUERRA, *IST Lisbon, Portugal* Low-energy electrons can interact with molecules via resonances to cause vibrational excitation with large cross-sections. Such processes can absorb significant energy from the plasma electrons, affecting the electron energy distribution and potentially (via vibration-translation (VT) energy transfer) causing substantial gas heating. The presence of vibrationally excited molecules may significant increase the rates of collisional processes, including electron dissociative attachment and electron impact dissociation into neutral atoms. However, the cross-sections of these processes are often poorly known since they are extremely difficult to measure directly, and reliable theoretical calculations are only now appearing for simple diatomic molecules. We have measured the vibrational distributions in discharges in pure O_2 and pure Cl_2, using high-sensitivity ultra-broadband ultraviolet absorption spectroscopy. In O_2 plasmas significant vibrational excitation is observed, up to v"=18, with a tail temperature of around 8000K. In Cl_2 excitation is only observed up to v"=3, and the distribution appears to be in local equilibrium with the gas translational temperature (up to 1500K). We are developing a detailed self-consistent 0D global model of these systems including vibrational excitation.

*Work performed in the LABEX Plas@par project, with financial state aid (ANR-11-IDEX-0004-02 and ANR-13-BS09-0019).

SESSION VF2: CAPACITIVELY COUPLED PLASMAS III

Friday Morning, 14 October 2016
Room: 2a at 11:00
Thomas Mussenbrock, Ruhr University, presiding

Contributed Papers

11:00

VF2 1 A Study on the Transient Behavior of Pulse Modulated Dual-Frequency Capacitive Discharges based on Circuit Analysis BYUNGKEUN NA, INSHIK BAE, GI JUNG PARK, HONG-YOUNG CHANG, *Korea Advanced Institute of Science and Technology (KAIST)* Multi-frequency capacitively coupled plasma (CCP) has been studied to independently control the ion energy and the ion flux; pulsing technique is used to reduce the electron temperature and finally the charging effects. The use of these techniques is a key to high aspect ratio contact (HARC) etching in the recent semiconductor processing. In this study, the characteristics of pulsed dual frequency (DF) CCP is investigated. Two separate powers of 3 MHz and 40 MHz are delivered to the powered electrode of an asymmetric CCP, and each frequency is modulated by an external 1 kHz pulse. Due to the complexity of the RF compensation in DF CCP, the characteristics of the plasma and the sheath are analyzed by high speed impedance measurement. The transient behavior of pulse modulated DF CCP is analyzed based on the result of continuous wave (CW) DF CCP. The optimized experimental condition for high ion energy will be presented. The difference between electronegative oxygen plasma and electropositive argon plasma is discussed as well.

11:15

VF2 2 Plasma Instability in Radio-Frequency Capacitively Coupled Discharge KALLOL BERA, ANKUR AGARWAL, SHAHID RAUF, JOHN FORSTER, *Applied Materials, Inc.* Stationary and moving striations with spatial periodic structure have been observed in radio-frequency (RF) capacitively coupled plasmas (CCP). To understand the striation mechanism, we have incorporated thermoelectric electron energy transport effect [1] in our fluid plasma model. The thermoelectric coefficient is calculated using Bolsig+ [2] for different chemistries, and is found to be the largest for Ar plasma. The thermoelectric effect reduces electron energy diffusion, which can localize the plasma and lead to periodic structures. To examine striations in capacitive plasmas, 2-dimensional Ar plasma at 13.5 MHz is first simulated without the thermoelectric effect. The charged species densities are then perturbed and growth or decay of different modes with time is observed. The periodicity of the structure is determined by the relative instability of different modes. Intermediate modes with periodicity of 4 to 15 cm are observed to grow while higher order modes decay. We will discuss effect of chemistry, power, pressure, and rf frequency to illustrate regimes where plasma instability may occur in typical CCP reactor geometries.

[1] D. Mackey *et al.*, Appl. Math. Lett. 865, (2005).
[2] G. J. M. Hagelaar and L. C. Pitchford, Plasma Sources Sci. Technol. 722 (2005).

11:30

VF2 3 High bias voltage plasma with electron beam INSHIK BAE, HONGYOUNG CHANG,* *Korea Adv Inst of Sci & Tech* A deep trench with high aspect ratio is required in the etch process, and it is well known that ion flux and energy can be independently controlled by means of dual or triple frequency. However, multi frequency capacitively coupled plasma (CCP) has a few problems to achieve high aspect ratio, such as surface charging and power coupling to bias voltage as well as interference between the frequencies. In this study, a new type of CCP, which is modified by using electron beam, is introduced. Low frequency of 400 kHz is used to generate plasma and to achieve high bias voltage in CCP. Electron beam, which is generated by thermal tungsten filament, is used to provide excess electrons. Because of excess electrons, the bias voltage of the powered electrode becomes extremely high to balance between electron and ion fluxes at the electrode. The effects of pressure, electron beam current, beam energy, and RF power in this phenomenon are carefully examined. A bias voltage which is almost same as a voltage amplitude of the RF power is obtained when enough number of electrons are supplied. This method can be used to generate high energy ions in etching process, and provides a more convenient and independent control of ion energy.

*Academic advisor.

11:45

VF2 4 Voltage vs. Current Driven CCRF Discharges: Differences in Electron and Ion Dynamics SEBASTIAN WILCZEK, JAN TRIESCHMANN, JULIAN SCHULZE,* RALF PETER BRINKMANN, *Ruhr University Bochum, Bochum, Germany* ARANKA DERZSI, PETER HARTMANN, ZOLTAN DONKO, *Wigner Research Center for Physics, Budapest, Hungary* THOMAS MUSSENBROCK, *Ruhr University Bochum, Bochum, Germany* In numerical simulations of capacitively coupled radio frequency (ccrf) discharges the following fundamental question is unanswered: What are the implications of driving the discharge with a sinusoidal current source vs. a sinusoidal voltage source? Several analytical models as well as simulations use current sources as boundary conditions. Especially at low pressures, however, the theory of the self-excitation of the plasma series resonance (PSR) by the nonlinearity of the plasma sheath is eliminated when using a current source (as no harmonics in the current are allowed). In contrast, a sinusoidal voltage source can strongly enhance the power dissipation via the self-excitation of the PSR (nonlinear electron resonance heating). In this work, we investigate the differences between voltage and current driven sources with respect to the electron and ion dynamics. By means of Particle-In-Cell simulations, we analyze both scenarios for identical input powers coupled into the system. Significant differences are discussed for different parameter sets, e.g. input power (voltage and current amplitude), driving frequency and pressure.

*West Virginia University, Morgantown, USA.

12:00

VF2 5 Investigation of plasma-sheath resonances in low pressure discharges* SCHABNAM NAGGARY, EFE KEMANECI, RALF PETER BRINKMANN, *Ruhr University Bochum* MUSTAFA MEGAHED, *ESI Group* Plasma sheath resonances (PSR) arise from a periodic exchange between the kinetic electron energy in the plasma bulk and the electric field energy in the sheath and can easily be excited by the sheath-generated harmonics of the applied RF. In this contribution, we employ a series of models to obtain a well-defined description of these phenomena. In the first part, we use a global model to study the influence of the nonlinear charge-voltage characteristics on the electron dynamics. However, the global model is restricted to the assumption of spatially constant potential at each driven and grounded electrode and thus delivers only the fundamental mode of the current. In order to remedy the deficiency, we introduce a spatially resolved model for arbitrary reactor geometries with no assumptions on the homogeneity of the plasma. An exact evaluation of the analytical solution is realized on the assumption of a cylinderical plasma reactor geometry with uniform conductance. Furthermore, the spatially resolved model is capable of being utilized for a more realistic CCP reactor geometry and non homogeneous plasma provided the conductance distribution is known. For this purpose, we use the CFD-ACE+ tool. The results show that the proposed multi-mode model provides a significant improvement.

*The authors gratefully acknowledge the financial support by the ESI Group and the SFB- TR 87.

12:15

VF2 6 Effect of driving frequency on the electron-sheath interaction and electron energy distribution function in a low pressure capacitively coupled plasmas SARVESHWAR SHARMA, *Institute for Plasma Research, Gandhinagar, Gujarat* NISHANT SIRSE, *School of Physical Sciences and NCPST, Dublin City University, Dublin 9, Ireland* PREDHIMAN KAW, *Institute for Plasma Research, Gandhinagar, Gujarat* MILES TURNER, ALBERT R. ELLINGBOE, *School of Physical Sciences and NCPST, Dublin City University, Dublin 9, Ireland* INSTITUTE FOR PLASMA RESEARCH, GANDHINAGAR, GUJARAT TEAM, SCHOOL OF PHYSICAL SCIENCES AND NCPST, DUBLIN CITY UNIVERSITY, DUBLIN 9, IRELAND COLLABORATION The effect of driving frequency (27.12-70 MHz) on the electron-sheath interaction and electron energy distribution function (EEDF) is investigated in a low pressure capacitive discharges using a self-consistent particle-in-cell simulation. At a fixed discharge voltage the EEDF evolves from a strongly bi-Maxwellian at low frequency, 27.12 MHz, to a convex type distribution at an intermediate frequency, 50 MHz, and finally becomes a weak biMaxwellian above 50 MHz. The EEDF evolution leads to a two-fold increase in the effective electron temperature up to 50 MHz, whereas the electron density remains constant in this range. After 50MHz, the electron density increases rapidly and the electron temperature decreases. The transition is caused by the transient electric field excited by bursts of high energy electrons interacting strongly with the sheath edge. Above the transition frequency, high energy electrons are confined between two sheaths which increase the ionization probability and thus the plasma density increases.

SESSION VF3: BIOLOGICAL APPLICATIONS OF PLASMA II
Friday Morning, 14 October 2016
Room: 2b at 11:00
Stephan Reuter, INP Greifswald, presiding

Contributed Papers

11:00

VF3 1 Generation of reactive oxygen and nitrogen species and its effects on DNA damage in lung cancer cells exposed to atmospheric pressure helium/oxygen plasma jets TAE HUN CHUNG, HEA MIN JOH, SUN JA KIM, JI YE CHOI, TAE-HONG KANG, *Dong-A University* We investigated the effects of the operating parameters on the generation of reactive oxygen and nitrogen species (RONS) in the gas and liquid phases exposed to atmospheric pressure a pulsed-dc helium plasma jets. The densities of reactive species including OH radicals were obtained at the plasma-liquid surface and inside the plasma-treated liquids using ultraviolet absorption spectroscopy and chemical probe method. And the nitrite concentration was detected by Griess assay. The data are very suggestive that there is a strong correlation among the production of RONS in the plasmas and liquids. Exposure of plasma to cancer cells increases the cellular levels of RONS, which has been linked to apoptosis and the damage of cellular proteins, and may also indirectly cause structural damage to DNA. To identify the correlation between the production of RONS in cells and plasmas, various assay analyses were performed on plasma treated human lung cancer cells (A549) cells. In addition, the effect of additive oxygen gas on the plasma-induced oxidative stress in cancer cells was investigated. It was observed that DNA damage was significantly increased with helium/oxygen plasma compared to with pure helium plasma.

11:15

VF3 2 Biological decontamination of surfaces using guided ionization waves JULIEN JARRIGE, CLEMENT ZAEPFFEL, *ONERA* Atmospheric pressure plasma jets have received an increasing attention these last ten years in various domains, including biomedical applications and decontamination. Among these technologies, guided ionization waves (also called "plasma bullets") are very promising because of their ability to produce a highly non-equilibrium plasma. Reactive species can be generated in the open air over a long distance during the propagation of the wave (typically: several cm), while the background gas remains at ambient temperature. A non-thermal plasma system has been developed and tested for the biological decontamination of surfaces. It consists of a dielectric barrier discharge in a helium flow driven by high voltage pulses. The propagation of the ionization wave and the spatial distribution of the species have been characterized by high speed imaging and optical emission spectroscopy. The influence of the discharge parameters on the plasma properties is investigated. Results of decontamination on several bacteria are shown, and the decontamination efficiency is compared with the plasma properties.

11:30

VF3 3 Bactericidal active ingredient in cryopreserved plasma-treated water with the reduced-pH method for plasma disinfection* KATSUHISA KITANO, *Eng., Osaka Univ.* SATOSHI IKAWA, YOICHI NAKASHIMA, *TRI Osaka* ATSUSHI TANI, *Sci., Osaka Univ.* TAKASHI YOKOYAMA, *Eng., Osaka Univ.* TOMOKO OHSHIMA, *Dental Medicine, Tsurumi Univ.* For the plasma disinfection of human body, plasma sterilization in liquid is crucial. We found that the plasma-treated water (PTW) has strong bactericidal activity under low pH condition. Physicochemical properties of PTW is discussed based on chemical kinetics. Lower temperature brings longer half-life and the bactericidal activity of PTW can be kept by cryopreservation. High performance PTW, corresponding to the disinfection power of 22 log reduction (*B. subtilis* spore), can be obtained by special plasma system equipped with cooling device. This is equivalent to 65% H_2O_2, 14% sodium hypochlorite and 0.33% peracetic acid, which are deadly poison for human. But, it is deactivated soon at higher temperature (4 sec. at body temperature), and toxicity to human body seems low. For dental application, PTW was effective on infected models of human extracted tooth. Although PTW has many chemical components, respective chemical components in PTW were isolated by ion chromatography. In addition to peaks of H_2O_2, NO_2^- and NO_3^-, a specific peak was detected. and only this fraction had bactericidal activity. Purified active ingredient of PTW is the precursor of HOO, and further details will be discussed in the presentation.

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

11:45

VF3 4 Mechanisms of selective antitumor action of cold atmospheric plasma DAVID GRAVES, *University of California at Berkeley* GEORG BAUER, *University Medical Center Freiburg, Germany* Transformed (precancerous) cells are known to be subject to elimination through intercellular RONS-dependent apoptosis-inducing signaling. It is a remarkable fact that the chemical species utilized by apoptosis induction in transformed cells are essentially identical to chemical species created by cold atmospheric plasma (CAP) in aqueous solutions. The association between CAP-induced biochemistry and natural cell anti-tumor mechanisms offers the opportunity to establish a rationale for the observed successes of CAP in selectively eliminating tumor cells in vitro and in vivo. In particular, 1O2 appears to act to selectively induce apoptosis in tumor cells, and can also result in self-perpetuating, cell-to-cell apoptotic signaling. Various CAP-generated liquid phase species can react to form 1O2, thus providing a hypothetical mechanism to explain how CAP can trigger therapeutic apoptosis in tumors. The analysis of model experiments performed with defined RONS in vitro implies that CAP-derived 1O2 induces the mechanism through which CAP acts selectively against cancer cells in vitro and tumors in vivo. This hypothesis needs to be tested experimentally in order to establish its validity.

12:00

VF3 5 Membrane Deformation and Permeabilization Caused by Microplasma Irradiation* HIDEKI MOTOMURA, HIDENORI NAGAIWA, KENTA YAMAMOTO, *Ehime University* YUGO KIDO, *Pearl Kogyo Co., Ltd.* YOSHIHISA IKEDA, *Ehime University* SUSUMU SATOH, *Y's Corp.* MASAFUMI JINNO, *Ehime University* The microplasma irradiation achieves high gene taransfection efficiency and high cell survivability simultaneously. For this purpose, we have developed a special plasma source using a microcapillary electrode. However, it is not clear how the stimuli of effective factors generated by plasma, such as current, charge, field, chemical species, cause transfection. In this study, we used artificial cell which is a spherical vesicle consisting of a lipid bilayer to visualize membrane dynamics and permeabilization caused by microplasma irradiation. Dioleoyl phosphatidylcholine (DOPC) was used as phospholipid molecules forming the lipid bilayer. The artificial cells were prepared by natural swelling method. Fluorescent labeled polyethylene glycol (PEG) polymers (Nanocs, MPEG Fluorescein, MW = 1000) were encapsulated in the artificial cells. The artificial cells were exposed to the microplasma for 5 ms and 10–20% of decrease of the dye fluorescence in the artificial cells was observed. This result suggests the outflow of the MPEG polymers through temporary poration or deformation of the lipid bilayer. The membrane deformation dynamics was directly observed with a microscope and the relationship to the polymer outflow will be shown at the conference.

*This work was partly supported by a Grant-in-Aid (25108509 and 15H00896) from JSPS and a grant from Ehime University.

12:15

VF3 6 Investigating the cell death mechanisms in primary prostate cancer cells using low-temperature plasma treatment* DEBORAH O'CONNELL, A M HIRST, *York Plasma Institute, University of York* J R PACKER, *Cancer Research Unit, University of York* M S SIMMS, V M MANN, *Dep. of Urology, Castle Hill Hospital & Hull York Medical School, University of Hull* F M FRAME, N J MAITLAND, *Cancer Research Unit, University of York* Atmospheric pressure plasmas have shown considerable promise as a potential cancer therapy. An atmospheric pressure plasma driven with kHz kV excitation, operated with helium and oxygen admixtures is used to investigate the interaction with prostate cancer cells. The cytopathic effect was verified first in two commonly used prostate cancer cell lines (BPH-1 and PC-3 cells) and further extended to examine the effects in paired normal and tumour prostate epithelial cells cultured directly from patient tissues. Through the formation of reactive species in cell culture media, and potentially other plasma components, we observed high levels of DNA damage, together with reduced cell viability and colony-forming ability. We observed differences in response between the prostate cell lines and primary cells, particularly in terms of the mechanism of cell death. The primary cells ultimately undergo necrotic cell death in both the normal and tumour samples, in the complete absence of apoptosis. In addition, we provide the first evidence of an autophagic response in primary cells. This work highlights the importance of studying primary cultures in order to gain a more realistic insight into patient efficacy.

*EPSRC EP/H003797/1 & EP/K018388/1, Yorkshire Cancer Research: YCR Y257PA.

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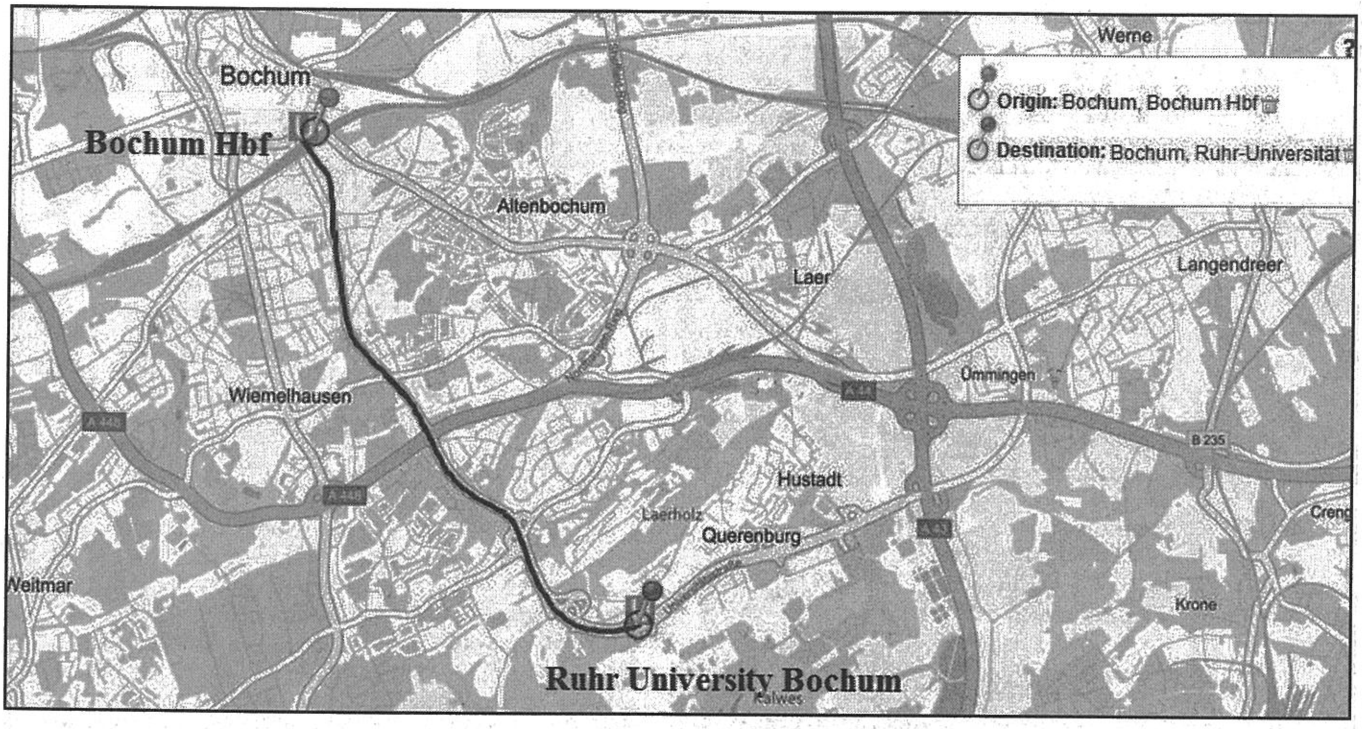
NOTES

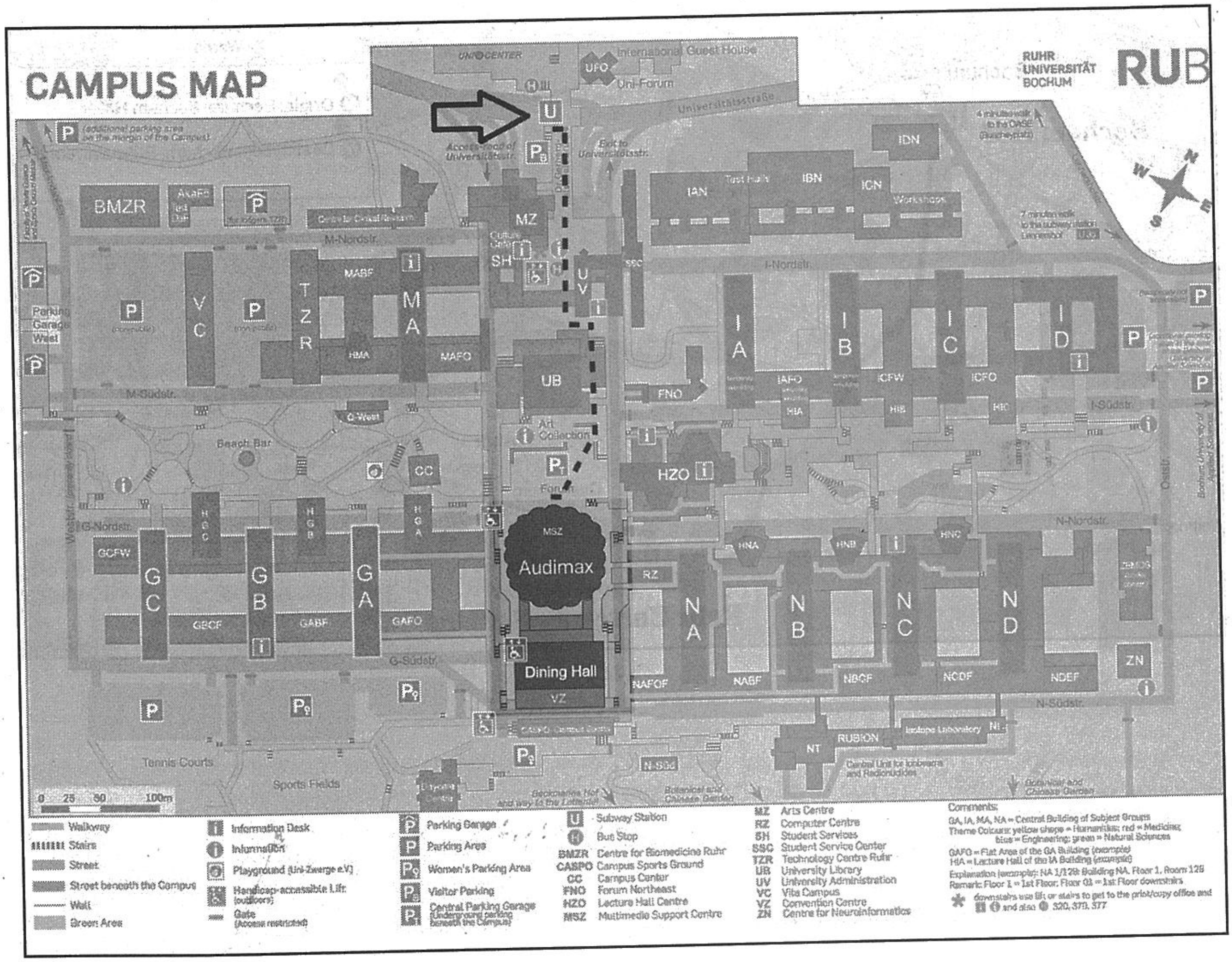
BOCHUM

Road Map



RUHR UNIVERSITY BOCHUM

Campus Map



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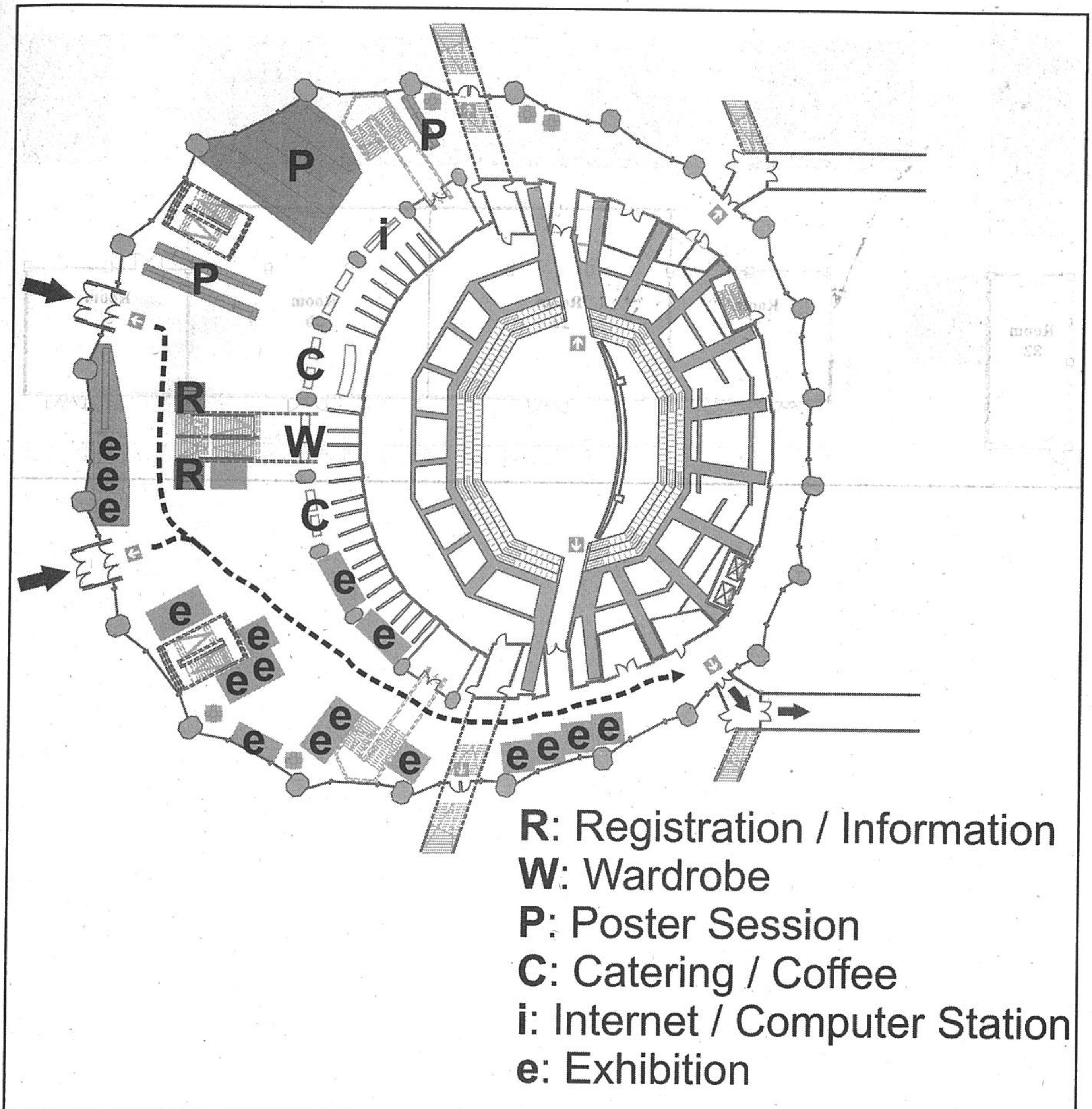

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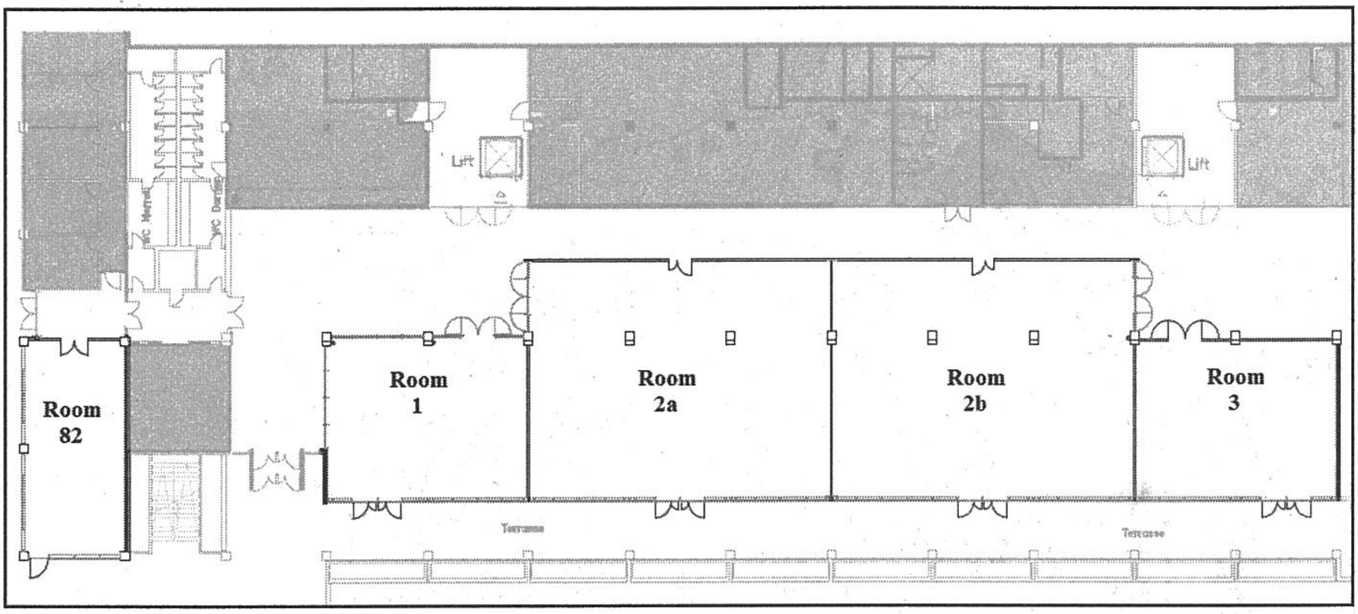
Rooms



TR2 **Magnetrons II**
Room: 2a

TR3 **High Pressure Plasma Chemistry**
Room: 2b

TR4 **Atmospheric Plasma Jets and Sources II**
Room: 3

18:00 THURSDAY EVENING
13 OCTOBER 2016

TR6 **Reception and Banquet**
Room: Henrichs Gebläsehalle, Hattingen

08:30 FRIDAY MORNING
14 OCTOBER 2016

UF1 **Electron-Impact Collisions**
Alexander Dorn, C. P. Ballance
Room: 1

UF2 **Chemical Modeling**
Jan van Dijk, Mario Capitelli
Room: 2a

UF3 **Thermal Plasmas**
Room: 2b

11:00 FRIDAY MORNING
14 OCTOBER 2016

VF1 **Electron Collisions with Small Molecules**
Leigh Hargreaves, Åsa Larson
Room: 1

VF2 **Capacitively Coupled Plasmas III**
Room: 2a

VF3 **Biological Applications of Plasma II**
Room: 2b

Epitome of the 2016 Annual Fall Meeting of the Gaseous Electronics Conference

10:00 MONDAY MORNING
10 OCTOBER 2016

BM1 **Electrification of the Chemical Industry**
David Graves, Richard van de Sanden, Ming Chen, Gerard van Rooij, Vasco Guerra, Rune Ingels, Sander van Bavel, Laurent Fulcheri, Ali Mesbah, Jurgen Lang
Room: Room 1

11:00 MONDAY MORNING
10 OCTOBER 2016

AM2 **Plasma Kinetics**
Ron White, Gerjan Hagelaar, Helge Redvald Skullerud, Sasa Dujko, Jens Oberrath, Lee Chen
Room: Room 2a

AM3 **Pulsed High Power Plasmas for Synthesis of Nanostructured Thin Films**
Arutiun Ehiasarian, Diederik Depla, Grzegorz Greczynski, Kostas Sarakinos, Tiberiu Minea, Christian Maszl, Nikolay Britun
Room: Room 2b

13:00 MONDAY AFTERNOON
10 OCTOBER 2016

BM3 **Future Challenges in Plasma Physics**
Gerrit Kroesen, Pascal Chabert, Igor Kaganovich, Luis Alves, Bill Graham, Peter Bruggeman, Michael Bonitz, Thomas Klinger, Masaru Hori, Yi-Kang Pu, Mark Kushner
Room: Room 3

18:00 MONDAY AFTERNOON
10 OCTOBER 2016

CM1 **Opening Reception**
Room: Foyer

08:30 TUESDAY MORNING
11 OCTOBER 2016

DT1 **Electrical Diagnostics I**
Alan Howling
Room: 1

DT2 **Computational Plasma Modeling**
Room: 2a

DT3 **Chemical Kinetics/Combustion & Environmental**
Nikolay Popov
Room: 2b

11:00 TUESDAY MORNING
11 OCTOBER 2016

ET1 **Negative Ion Complex, and Dust Particle Containing Plasmas**
Room: 1

ET2 **Sheaths/Plasma Physics**
Greg Severn
Room: 2a

ET3 **Plasma Liquid Interactions**
Keisuke Takashima, Toshiro Kaneko
Room: 2b

14:00 TUESDAY AFTERNOON
11 OCTOBER 2016

FT1 **Optical Emission Spectroscopy**
Room: 1

FT2 **Inductively Coupled Plasmas I**
Room: 2a

FT3 **Microplasmas**
Ayyaswamy Venkattraman
Room: 2b

FT4 **Plasma Deposition I**
Room: 3

16:00 TUESDAY AFTERNOON
11 OCTOBER 2016

GT1 **Plasma Propulsion and Aerospace Applications I**
Christine Charles
Room: 1

GT2 **Capacitively Coupled Plasmas I**
Room: 2a

GT3 **Discharges in Liquids I**
Tsuyohito Ito
Room: 2b

GT4 **Magnetrons I**
Room: 3

17:30 TUESDAY EVENING
11 OCTOBER 2016

HT6 **Poster Session I**
Room: Foyer

08:30 WEDNESDAY MORNING
12 OCTOBER 2016

JW1 **Antimatter Collisions and Ionization Processes**
Gaetana Laricchia, Lorenzo Ugo Ancarani
Room: 1

JW2 **Capacitively Coupled Plasmas II**
Aranka Derzsi
Room: 2a

JW3 **Atmospheric Plasma Jets and Sources I**
Sander Nijdam
Room: 2b

JW4 **Plasma Propulsion and Aerospace Applications II**
Room: 3

10:30 WEDNESDAY MORNING
12 OCTOBER 2016

KW1 **The Will Allis Prize for the Study of Ionized Gases**
Klaus Bartschat
Room: 1

17:30 WEDNESDAY EVENING
12 OCTOBER 2016

MW6 **Poster session II**
Room: Foyer

15:00 WEDNESDAY AFTERNOON
12 OCTOBER 2016

NW1 **Laser-Based Diagnostics I**
Edward Barnat
Room: 1

NW2 **Plasma Etching**
Hisataka Hayashi
Room: 2a

NW3 **Surface and Dielectric Barrier Discharges**
Room: 2b

NW4 **Basic Plasma Physics I**
Room: 3

08:30 THURSDAY MORNING
13 OCTOBER 2016

QR1 **Heavy Particle Collisions**
Xavier Urbain, Luis Mendez
Room: 1

QR2 **Plasma Surface Interaction**
Masaaki Matsukuma, Shahid Rauf
Room: 2a

QR3 **Streamer and Breakdown Processes**
Zdeněk Bonaventura
Room: 2b

QR4 **Basic Plasma Physics II**
Peter Hartmann
Room: 3

11:00 THURSDAY MORNING
13 OCTOBER 2016

RR1 **Electrical Diagnostics II**
Keiji Nakamura
Room: 1

RR2 **Plasma Deposition II**
Room: 2a

RR3 **Discharges in Liquids II**
Room: 2b

RR4 **Electro-Magnetic Interactions with Plasmas I**
Jeffrey Hopwood
Room: 3

14:00 THURSDAY AFTERNOON
13 OCTOBER 2016

SR1 **Electron-Molecule Collision Data for Plasma Modelling**
Michael Brunger, Jonathan Tennyson
Room: 1

SR2 **Inductively Coupled Plasmas II**
Room: 2a

SR3 **Biological Applications of Plasma I**
Masafumi Jinno
Room: 2b

SR4 **Electro-Magnetic Interactions with Plasmas II**
Room: 3

16:00 THURSDAY AFTERNOON
13 OCTOBER 2016

TR1 **Laser-Based Diagnostics II**
Thomas Trottenberg
Room: 1

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