BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

67th Annual
Gaseous Electronics Conference

November 2-7, 2014
Raleigh, North Carolina

Volume 59, Number 9

APS physics

BULLETIN OF THE AMERICAN PHYSICAL SOCIETY

Coden BAPSA6 ISSN: 0003-0503
Series II, Vol. 59, No. 16 October 2014

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

66th Annual Gaseous Electronics Conference

Table of Contents

67th Annual Gaseous Electronics Conference

November 3–7, 2013
Raleigh, North Carolina

GENERAL INFORMATION

On behalf of the executive committee and local organizing committee, welcome to Raleigh, North Carolina. As part of the research triangle that also comprises Chapel Hill and Durham, we are excited to highlight the academic, commercial, and cultural contributions of our region. Downtown Raleigh is an ideal location for an early November meeting, with excellent weather, fall color, and abundant amenities within walking distance of the City Center Marriott that include a wide array of restaurants, museums, art galleries, theaters, and sporting events. Venturing outside the pedestrian friendly downtown opens up exciting regional attractions including several top tier research universities and liberal arts colleges, the North Carolina Museum of Art, Duke Gardens, and the nearby cities of Durham and Chapel Hill.

The 67th Gaseous Electronics Conference (GEC) of the American Physical Society is being held at the Marriott City Center and Raleigh Convention Center in the heart of downtown Raleigh. The conference is adjacent to the commercial centers of Fayetteville Street, Wilmington Street, and City Market. During the conference there are several events scheduled near the hotel including walking tours of Raleigh restaurants, farmer's markets, and live bluegrass music. On the last day of the conference, downtown Raleigh will come alive with the monthly First Friday's event featuring street performances and art galleries open until late at night. Expect to have a busy week both during and after the technical sessions.

The conference will bring together over 400 scientists and engineers from around the world who will attend 31 invited talks, 190 oral contributed talks, and 155 poster presentations. The GEC technical program includes the Allis Prize Talk, two daylong preconference workshops on Monday, an opening reception on Monday evening, two focus sessions on Tuesday morning, and a Thursday evening awards banquet, all held in ample facilities capable of accommodating breakout sessions, meetings, and interviews.

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

The GEC will also present the "Student Award for Excellence" to the best student oral presentation, selected from a group of four finalists.

SPECIAL SESSIONS AND EVENTS

TThe GEC Executive Committee is pleased to announce that the Allis Prize Talk will be presented by David Graves from the University of California at Berkeley. His talk entitled "Future low temperature plasma science and technology: attacking major societal problems by building on a tradition of scientific rigor" will be given at 10:30 am on Wednesday, November 5 in the State Ballroom.

Two daylong workshops will be held on Monday, November 3:

SESSION AM1:
Advanced RF Systems for Plasma Control
Date: Monday, November 3 (starts at 8 am)
Organizers: David J. Coumou, ENI Products, MKS Instruments Inc.

SESSION AM2:
Plasma Verification and Validation
Date: Monday, November 3 (starts at 8:00 am)
Organizers: Brooke S. Stutzman, U.S. Coast Guard Academy, John Verboncoeur, Michigan State University

Two additional focused topical sessions will be held on Thursday, November 6.

SESSION MR2:
Plasma Interactions with Liquid
Date: Thursday, November 6, 8am
Session Chair: Steve Shannon (NC State University)

SESSION MR3:
Plasma Enhanced Chemically Reactive Flows
Date: Thursday, November 6, 8am
Session Chair: Alexei Savaliev (NC State University)

GEC SESSIONS

Each session has a code consisting of a letter and a number. The first letter indicates the numbering for that session in the program, e.g., A for 1, B for 2, etc. The second letter indicates the day of the week, for example, M for Monday, T for Tuesday, W for Wednesday, R for Thursday, and F for Friday. The last number indicates the room location: 1 for State EF, 2 for State C, 3 for State B, and 4 for the Convention Center Ballroom that will house the poster sessions and welcome reception.

AM1 ....Workshop on Plasma Surface Interaction: From Fusion to Semiconductor Processing
AM2 ....Workshop on Weakly-ionized non-equilibrium air plasma at moderate and high pressures: generation and maintenance, modeling, diagnostics and applications

BM1 ....Welcome Reception

CT1 ....Poster Session I

DT1 ....Basic Phenomena in Low Temperature Plasma Physics
DT2 ....High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks I
DT3 ....Liquids I
DT4 ....Workshop on the Mysteries and Challenges of Negative Ion Sources

ET1 ....Glows: dc, pulsed, microwave, others
ET2................Microdischarges I
ET3................Green Plasma Technologies I
ET5................Workshop on the Plasma Data Exchange Project

FT1 ....Non-equilibrium Kinetics of Low-temperature Plasmas
FT2 ....High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks II
FT3 ....Liquids II

GT1 ....Tour of the Princeton Plasma Physics Laboratory

HW1 ....Poster Session II

IW1 ....PPPL Director Welcome and GEC Foundation Talk

JW1 ....GEC Business Meeting

KW1 ....Inductively Coupled Plasmas
KW2................Microdischarges II
KW3 ....Green Plasma Technologies II
KW5 ....Electron and Positron Collisions with Atoms

LW1................Plasma Etching
LW2................Plasma Modeling I
LW3................Biomedical Applications I
LW5................Heavy-Particle Collisions

MR1 ....Poster Session III

NR1 ....Diagnostics I
NR2................Plasma-surface Interactions
NR3 ....Plasma Boundaries: Sheaths, Boundary Layers, Others

PR1................High Pressure Discharges: Dielectric

CONFERENCE FORMAT

The GEC will host oral presentations in the State Ballrooms C, D, and EF on the first floor of the City Center Marriott in Raleigh NC. State Ballrooms A and B will host the conference exhibition floor featuring many of the GEC's corporate sponsors. The welcome reception and Tuesday/Wednesday poster sessions will be held in the Raleigh Convention Center, Ballrooms B and C, connected to the Raleigh Marriott via the underground connection between the two facilities (both escalator and elevator service is available in order to accommodate all facility needs). The banquet will be held at the Marriott in the State Ballroom on Thursday evening. Refreshments will be provided daily outside of the State ballrooms at 10am and 3:30pm. There will be two parallel sessions on Monday and three parallel sessions Tuesday morning through Friday at noon. There will be two poster sessions that will be held in the Raleigh Convention Center in Ballroom C on Tuesday and Wednesday evenings from 5:30pm to 7pm. Posters may remain on display until the end of each day.

PRESENTATION FORMAT

Papers that have been accepted for presentations are listed in the scientific program. Invited talks are allotted 25 minutes, with 5 additional minutes for questions and discussion. Oral contributed talks are allotted 12 minutes, with 3 additional minutes for questions and discussion. Poster boards measure 4 feet by 8 feet. The posters can remain on display throughout the day and should be removed at the close of each day. The special topic sessions on Thursday morning from 8am to 9:30am will be 15 minute presentations with an additional 5 minutes for questions and discussion.

GEC STUDENT AWARD FOR EXCELLENCE

The GEC Executive Committee will award a $1000 prize for best oral presentation by a student. Their advisor must have nominated a student before being selected by GEC Executive Committee members to present and compete for the Excellence Award. Student award finalists will present his or her work on Tuesday, November 4 and Wednesday November 5. Students competing for the award, in the order of their appearance in the GEC 2014 program are:

Andrew Gibson, Queen's University Belfast
"Tailoring plasma properties through the non-linear frequency coupling of odd harmonics"
Tuesday, November 4 at 3:30pm in State C

Georges Al Makdessi, University of Montreal
"Correlation between nanoparticles formation and plasma parameters evolution in magnetically confined C_2H_2/Ar plasma"
Wednesday, November 5 at 8:30am in State C

Mickael Foucher, Laboratoire de Physique des Plasmas, Centre national de la recherche scientifique
"Inductively-coupled plasmas in pure Cl, O and mixtures: measurements of atoms, Cl_xO_y and electron densities"

Wednesday, November 5 at 3:30pm in State EF.

At the 2013 GEC in Princeton New Jersey, the GEC Student Award for Excellence was presented to Arthur Greb, York Plasma Institute, Department of Physics, University of York, United Kingdom, for the oral presentation "The role of surface properties in the dynamics of radio-frequency plasma sheaths: measurements and simulations".

REGISTRATION

The registration desk will be open on Monday, November 3 from 4:00 pm to 7:00 pm in the foyer outside the Raleigh Convention Center Ballroom B. Tuesday through Friday the registration desk will be open from 7:30 am to 4:00 pm in the Congressional Ballroom in the Marriott City Center. The on-site registration fees are:

Regular Attendee	$575
Retired/Unemployed	$350
Student	$350
One-Day Attendee	$350
Guest Banquet Ticket	$65

OPENING RECEPTION AND BANQUET

An opening reception will be held from 7:00 pm to 9:00 pm on Monday, November 3 in the Convention Center Ballroom B. On Thursday evening, November 6 the banquet reception will be held at 6:00 pm in the hotel State Ballroom foyer followed by the banquet from 7:00 pm to 9:00 pm featuring live entertainment, award presentations, and the merciful omission of a banquet speaker. The cost of the banquet is included in the registration fee. Companion banquet tickets may be purchased for $65.00 at the registration desk on-site through the end of the day on Tuesday, November 4. All conference attendees and guests are encouraged to attend. The GEC Award for Student Excellence will be presented during the banquet.

WI-FI AND OTHER BUSINESS SERVICES

Wi-Fi access is complimentary in the sleeping rooms and meeting areas. For a fee, services such as faxing, printing and photocopying are available in the Business Center located on the 1st floor of the Marriott.

AUDIO-VISUAL EQUIPMENT

The technical sessions will be equipped with an LCD projector and amplified sound. Laptops will be provided for the technical sessions.

Talks will be uploaded via Dropbox to secure folders assigned to each author. All presentation laptops will be linked to the Dropbox account and equipped with Windows 7, Powerpoint, Acrobat, Quicktime, and Windows Media player.

CONFERENCE MOBILE APPLICATION

The GEC technical program and other vital points of interest for the conference is available on the conferences mobile application. The application is available for download at the Android store and iTunes and is most easily located by searching "Gaseous Electronics Conference."

DINING OPTIONS

The Marriott hotel has full service dining for breakfast, lunch, and dinner. The City Center Marriott is located in the heart of downtown Raleigh, with dozens of restaurants, bars, art galleries, and concert venues within short walking distance. Dining options are numerous, and exploring the many options within walking distance of the conference hotel is encouraged. Some of the host's recommended destinations can be found in the conference mobile application.

CALL FOR NOMINATIONS FOR GEC GENERAL AND EXECUTIVE COMMITTEES

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

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

Written proposals to host future GEC meetings are encouraged and should be discussed with the Chair of the Executive Committee. The General Committee reviews all proposals and makes the final site selection. The selected host is then elected to a 3-year term on the Executive Committee as Secretary-Elect, then Secretary, and finally as Past Secretary.

The 2014 Business Meeting will take place on Wednesday, November 5 immediately following the Allis Prize Lecture in the State Ballroom.

GEC 2014 EXECUTIVE COMMITTEE

Amy Wendt
Chair, University of Wisconsin

Mirko Vukovic
Chair-Elect, Tokyo Electron

Igor Kaganovich
Past Secretary, Princeton Plasma Physics Laboratory

Steve Shannon
Secretary, N.C. State University

Klaus Bartschat
Secretary Elect, Drake University

Tom Kirchner
Treasurer, York University

Jim Lawler
APS-DAMOP, University of Wisconsin

Greg Severn
University of San Diego

Ursel Fantz
Max-Planck-Institut für Plasmaphysik

Allison Harris
Illinois State University

Hirotaka Toyoda
Nagoya University

MEMBERS OF GEC 2014 LOCAL ORGANIZING COMMITTEE

Steve Shannon
NCSU

Mohamed Bourham
NCSU

David Coumou
MKS Instruments

John Gilligan
NCSU

Venkateswaran Narayanaswamy
NCSU

Patrick Pedrow
Washington State University

Alexei Savaliev
NCSU

J.P. Sheehan
University of Michigan

Saralyn Stewart
GEC Conference Manager

Brooke Stutzman
US Coast Guard Academy

Leigh Winfrey
Virginia Tech

GEC 2014 SPONSORS AND EXHIBITORS

Sponsors and Exhibitors allow the GEC Executive Committee to provide many benefits to attendees including travel assistance and an excellence award for junior attendees. The 67th GEC has been fortunate to receive support from the following organizations (up to the time of this publication.) GEC is very grateful for the continued support from government and industry.

US Government Agency and Laboratory Sponsors
NSF/DOE Partnership in Basic Plasma Science and Engineering
NSF program "Combustion and Fire Systems"
NSF program "AMO Experimental"
NSF program "AMO Theory"
Department of Energy, Office of Fusion Energy Sciences
Sandia National Laboratory

Non-government Sponsors

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IOP Publishing

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

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Epitome of the 2014 Annual Fall Meeting of the Gaseous Electronics Conference

08:00 MONDAY MORNING
03 NOVEMBER 2014

AM1 **Advanced RF Systems for Plasma Control**
David Coumou
Room: State EF

AM2 **Workshop: Plasma Verification and Validation**
J.P. Verboncoeur, Andrew Christlieb, Miles Turner, L.C. Pitchford, Keigh Cartwright, Christopher Roy, William Rider
Room: State C

08:00 TUESDAY MORNING
04 NOVEMBER 2014

CT1 **Plasma Boundaries, Sheaths, and Basic Plasma Physics I**
Scott D. Baalrud
Room: Ballroom EF

CT2 **Propulsion and Aerodynamics**
Amnon Fruchtman, Ane Aanesland
Room: State C

CT3 **Plasma Chemistry**
Room: State D

10:00 TUESDAY MORNING
04 NOVEMBER 2014

DT1 **Plasma Diagnostics I**
John B. Boffard
Room: State EF

DT2 **Plasma Modeling and Simulations I**
Room: State C

DT3 **Effects of Plasmas on Biological Cells**
Nevena Puac, Toshiro Kaneko
Room: State D

13:30 TUESDAY AFTERNOON
04 NOVEMBER 2014

ET1 **Plasma Diagnostics and Sources for Biological Applications**
Room: State EF

ET2 **Modeling of Plasma Etching**
Koji Eriguchi
Room: State C

ET3 **Dielectric Barrier Discharges and Corona**
Jose L. Lopez
Room: State D

15:30 TUESDAY AFTERNOON
04 NOVEMBER 2014

FT1 **Plasma Surface Interactions**
Scott Kovaleski
Room: State EF

FT2 **Capacitive Discharges - Computational**
Kallol Bera
Room: State C

FT3 **Graphene Synthesis; Plasma Light Generation**
Room: State C

17:30 TUESDAY EVENING
04 NOVEMBER 2014

GT1 **Poster Session I (17:30-19:30)**
Exhibit Hall

08:00 WEDNESDAY MORNING
05 NOVEMBER 2014

HW1 **Non-equilibrium Kinetics and Basic Plasma Physics of Low Temperature Plasmas**
Room: Ballroom EF

HW2 **Dusty Plasmas and Negative Ions**
Room: State C

HW3 **Plasma Interactions with Biological Surfaces**
Michael Kong
Room: State D

10:00 WEDNESDAY MORNING
05 NOVEMBER 2014

JW1 **The Will Allis Prize for the Study of Ionized Gases**
David Graves
Room: State EF

11:00 WEDNESDAY MORNING
05 NOVEMBER 2014

JW2 **GEC Business Meeting**
Room: State AB

13:30 WEDNESDAY AFTERNOON
05 NOVEMBER 2014

KW1 **Plasma Diagnostics II**
Kenji Ishikawa
Room: State EF

KW2 **Reactive Microdischarges**
Room: State C

KW3 **Electron-Molecule Collisions and Related Processes I**
Nicholas Shuman, Darryl Jones
Room: State D

15:30 WEDNESDAY AFTERNOON
05 NOVEMBER 2014

LW1 **Plasma Diagnostics III**
Room: State EF

LW2 **Plasmas in Liquids**
Room: State C

LW3 **Electron-Molecule Collisions and Related Processes II**
Sylwia Ptasinska, Daniel Slaughter
Room: State D

17:30 WEDNESDAY EVENING
05 NOVEMBER 2014

MW1 **Poster Session II (17:30-19:30)**
Exhibit Hall

08:00 THURSDAY MORNING
06 NOVEMBER 2014

MR2 **Plasma Interactions with Liquid**
David B. Go, Paul Rumbach, David Bartels, R. Mohan Sankaran, Mark Kushner, Peter Bruggerman, Zachary Taillefer, John Blandin, James Szabo
Room: State C

MR3 **Plasma Enhanced Chemically Reactive Flows**
Igor V. Adamovich, Walter R. Lempert, Sergey Lenonov, Andrey Starikovskiy, Hyungrok Do, Campbell D. Carter
Room: State D

10:00 THURSDAY MORNING
06 NOVEMBER 2014

NR1 **Plasma Boundaries, Sheaths, and Basic Plasma Physics II**
Scott Robertson, J. P. Sheehan
Room: State EF

NR2 **Magnetically Enhanced Plasmas**
Andrei Smolyakov, John Forster
Room: State C

NR3 **Heavy Particle Collisions**
Alisher Kadyrov, Sebastian Otranto
Room: State D

13:30 THURSDAY AFTERNOON
06 NOVEMBER 2014

PR1 **Microdischarge Devices**
Room: State EF

PR2 **Plasma Deposition and Nanoparticle Generation**
Rebecca Anthony
Room: State C

PR3 **Coronal and HV Discharges**
Room: State D

15:30 THURSDAY AFTERNOON
06 NOVEMBER 2014

QR1 **Plasma Modeling and Simulations II**
Room: State EF

QR2 **Plasma Applications in Accelerator Technology**
Thomas Katsouleas,
Svetozar Popovic
Room: State D

QR3 **Collisions Involving Antimatter Particles and Atoms**
J. R. Danielson,
Michael Charlton
Room: State D

08:30 FRIDAY MORNING
07 NOVEMBER 2014

SF1 **Plasma Sources**
Lee Chen
Room: State EF

SF2 **Thermal and Microwave Plasmas**
Mikhail Shneider
Room: State C

SF3 **Electron Collisions with Atoms and Molecules**
James Colgan,
Jimena Gorfinkiel
Room: State D

SESSION AM1: ADVANCED RF SYSTEMS FOR PLASMA CONTROL

Monday Morning, 3 November 2014; Room: State EF at 8:00; David Coumou, MKS Instruments, presiding

Invited Papers

8:00
AM1 1 Introduction
DAVID COUMOU, *MKS Instruments*

8:15
AM1 2 Time-Modulated Inductively Coupled Plasmas for Advanced Dry Etching Processes
WAHEB BISHARA, SAMER BANNA, *Applied Materials Inc.*

9:00
AM1 3 The Electrical Asymmetry Effect in capacitive RF plasmas: Past, Present, and Future
J. SCHULZE, A. DERZSI, I. KOROLOV, S. BRANDT, Z. DONKO, *West Virginia University; Hungarian Academy of Sciences*

9:45
AM1 4 Break

10:15
AM1 5 Control of Ion Energy Distributions Through the Phase Difference Between Multiple Frequencies in Capacitively
YITING ZHANG, MARK J. KUSHNER, *University of Michigan*

11:00
AM1 6 EEDf, IEDf and some of the physics of the Non-ambipolar Electron Plasma (NEP)
LEE CHEN, ZHIYING CHEN, *Tokyo Electron America, Inc.*

11:45
AM1 7 Lunch

13:00
AM1 8 Centralized and Coherent Feedforward Impedance Tuning Control and Feedback Power Regulation for the Enhancement of RF Plasma Processing Systems
DAVID COUMOU, *MKS Instruments*

13:45
AM1 9 Inductively Coupled Plasma Sources for Dry Etching and Annealing Processes
TOMOHIRO OKUMURA, *Panasonic*

14:30
AM1 10 Panel Discussion

SESSION AM2: WORKSHOP: PLASMA VERIFICATION AND VALIDATION

Monday Morning, 3 November 2014; Room: State C at 8:00; John Verboncoeur, Michigan State University, presiding

Invited Papers

8:00
AM2 1 Validation and Verification with Applications to a Kinetic Global Model*
J.P. VERBONCOEUR, *Michigan State University*

As scientific software matures, verification, validation, benchmarking, and error estimation are becoming increasingly important to ensure predictable operation. Having well-described and consistent data is critical for consistent results. This presentation briefly addresses the motivation for V&V, the history and goals of the workshop series. A roadmap of the current workshop is presented. Finally, examples of V&V are applied to a novel kinetic global model for a series of low temperature plasma problems ranging from verification of specific rate equations to benchmarks and validation with other codes and experimental data for Penning breakdown and hydrocarbon plasmas. The results are included in the code release to ensure repeatability following code modifications. In collaboration with G. Parsey, J. Kempf, and A. Christlieb, Michigan State University.

*This work is supported in part by a U.S. Air Force Office of Scientific Research Basic Research Initiative and a Michigan State University Strategic Partnership grant.

8:50
AM2 2 Verification and Validation of Kinetic Codes
ANDREW CHRISTLIEB, *Michigan State University*

We review the last three workshops held on Validation and Verification of Kinetic Codes. The goal of the workshops was to highlight the need to develop benchmark test problems beyond traditional test problems such as Landau damping and the two-stream instability. These test problems provide a limited understanding how a code might perform and mask key issues in more complicated situations. Developing these test problems highlights the strengths and weaknesses of both mesh- and particle-based codes. One outcome is that designing test problems that clearly deliver a path forward for developing improved methods is complicated by the need to create a completely self-consistent model. For example, two test cases proposed by the authors as simple test cases turn out to be ill defined. The first case is the modeling of sheath formation in a 1D 1V collisionless plasma. We found that losses to the wall lead to discontinuous distribution functions, a challenge for high order mesh-based solvers. The semi-infinite case was problematic because the far field boundary condition poses difficulty in computing on a finite domain. Our second case was flow of a collisionless electron beam in a pipe. Here, numerical diffusion is a key problem we are testing; however, two-stream instability at the beam edges introduces other issues in terms of finding convergent solutions. For mesh-based codes, before particle trapping takes place, mesh-based methods find themselves outside of the asymptotic regime. Another conclusion we draw from this exercise is that including collisional models in benchmark test problems for mesh-based plasma simulation tools is an important step in providing robust test problems for mesh-based kinetic solvers. In collaboration with Yaman Guclu, David Seal, and John Verboncoeur, Michigan State University.

9:40
AM2 3 Break

10:00
AM2 4 Benchmark solutions for simulations of capacitively coupled discharges
MILES TURNER, *Dublin City University*

Benchmarks are an important element of Verification and Validation strategies. Such strategies define a process for increasing confidence in the fidelity of computer simulations, with the aim of making confident predictions of physical behaviour under conditions of practical interest. Such confidence can be increased by developing benchmark solutions for representative conditions. A benchmark solution is a high quality solution that is accepted to be correct. In this paper, we describe an attempt to develop such solutions for capacitive discharges, and we show that a number of independently developed particle-in-cell simulations can reproduce the benchmark solutions. These solutions are useful not only for particle-in-cell simulations, but also for other kinds of plasma simulations. We will show comparisons of fluid model solutions with the benchmarks.

10:50
AM2 5 LXCat: A web-based, community-wide project on data for modeling low temperature plasmas
L.C. PITCHFORD, *LAPLACE (Laboratoire Plasma et Conversion d'Energie); CNRS and Universite de Toulouse*

LXCat is an open-access website (www.lxcat.net) for exchanging data related to ion and electron transport and scattering cross sections in cold, neutral gases. At present 30 people from 12 countries have contributed to the LXCat project. This presentation will focus on the status of the data available for electrons on LXCat. These data are primarily in the form of "complete" sets of cross sections, compiled or calculated by different contributors, covering a range of energies from thermal up to about 1 keV. The cross section data can be used directly in Monte Carlo simulations and can also be used as input to Boltzmann equation solvers. Solution of the homogeneous, steady-state Boltzmann equation yields electron energy distribution functions (edf) as a function of reduced electric field strength, E/N, integrals over which yield electron transport and rate coefficients. The transport and rate coefficient data are required input for fluid models of low temperature plasmas. Evaluation of the cross section data sets available on LXCat is a key issue. To this end, the LXCat team has been making systematic intercomparisons of cross section data and comparisons of calculated and measured transport and rate coefficients. Our evaluations have been reported previously for noble gases and for common atmospheric gases. The LXCat team is now evaluating data for more complex molecules.

11:40
AM2 6 Lunch

13:10
AM2 7 Richardson Extrapolation Based Error Estimation for Stochastic Kinetic Plasma Simulations*
KEIGH CARTWRIGHT, *Sandia National Laboratories*

To have a high degree of confidence in simulations one needs code verification, validation, solution verification and uncertainty qualification. This talk will focus on numerical error estimation for stochastic kinetic plasma simulations using the Particle-In-Cell (PIC) method and how it impacts the code verification and validation. A technique Is developed to determine the full converged solution with error bounds from the stochastic output of a Particle-In-Cell code with multiple convergence parameters (e.g. ?t, ?x, and macro particle weight). The core of this method is a multi parameter regression based on a second-order error convergence model with arbitrary convergence rates. Stochastic uncertainties in the data set are propagated through the model usin gstandard bootstrapping on a redundant data sets, while a suite of nine regression models introduces uncertainties in the fitting process. These techniques are demonstrated on Flasov-Poisson Child-Langmuir diode, relaxation of an electro distribution to a Maxwellian due to collisions and undriven sheaths and pre-sheaths.

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

14:00
AM2 8 The Role of V&V in Total Prediction Uncertainty
CHRISTOPHER ROY, *Aerospace and Ocean Engineering Department, Virginia Tech*

Computational Fluid Dynamics (CFD) simulations are frequently used for decision making in scientific and engineering systems. However, the accuracy and reliability of CFD simulations is often poorly understood. There are three sources of uncertainty in CFD predictions: uncertainty in model inputs, uncertainty due to numerical errors, and uncertainty due to modeling errors. When model input uncertainties are stochastic, they are appropriately described by precise probability distributions, and their effects on output quantities are often determined by standard techniques. In general, not all inputs have precisely specified probability distributions. In such cases, different techniques, such as segregated uncertainty propagation, are needed to propagate mixed aleatory and epistemic uncertainty. Verification and Validation (V&V) address the processes used to estimate uncertainties due to numerical errors and modeling errors, respectively. During Verification, one estimates the numerical errors in a simulation. This estimation process leads one to treat these as uncertainties; however, they are not random (aleatory) uncertainties, but are instead lack of knowledge (epistemic) uncertainties. During Validation, one estimates the errors due to model form. This process usually involves comparison of nondeterministic outcomes from simulation and experiment the estimation process leads us to treat the modeling errors as uncertainties. Finally, estimating the total prediction uncertainty requires that all three sources be accounted for: input uncertainty (via uncertainty propagation), numerical uncertainty (via Verification), and model form uncertainty (via Validation).

14:50
AM2 9 Break

15:10
AM2 10 What is Necessary To Succeed in V&V? Experience From The DOE ASC V&V Program
WILLIAM RIDER, *Sandia National Laboratories*

Verification and validation is a route toward examining the credibility and confidence in computations. These are interdependent and complementary activities that are usually combined with uncertainty quantification. Validation is usually the emphasis for most scientific endeavors being predicted upon experimental science and physical theory. Verification is similarly based upon the mathematical basis of the numerical methods. Upon this point PIC methods in particular are disadvantaged as the mathematical basis is quite weak. Nonetheless useful empirical results can be examined. A great deal of experience has been gained in the application of a systematic V&V process including uncertainty quantification. The lessons from these efforts can be applied profitably to PIC methods.

16:00
AM2 11 Panel Discussion

SESSION CT1: PLASMA BOUNDARIES, SHEATHS, AND BASIC PLASMA PHYSICS I

Tuesday Morning, 4 November 2014; Room: Ballroom EF at 8:00; JP Sheehan, Plasmadynamics & Electric Propulsion Laboratory, University of Michigan, presiding

Invited Papers

8:00

CT1 1 The Plasma-Sheath Boundary in Two-Ion-Species Plasmas*

SCOTT D. BAALRUD, *Department of Physics and Astronomy, University of Iowa*

The Bohm criterion is among the most important results in plasma physics because it provides the ion flow speed at the sheath edge under common plasma conditions. This is a useful boundary condition for modeling plasma-materials interactions, as well as for global plasma models. However, a difficulty arises when multiple ion species are present because the Bohm criterion provides only one constraint in as many unknowns as there are ion species. Conventional theory assumes that the ion species are decoupled, which leads to the prediction that each obtains its individual sound speed at the sheath edge: $V_i = \sqrt{T_e/m_i}$. However, experiments in Ar-Xe and He-Xe mixtures have revealed that the ion speeds can merge toward a common speed under typical low-temperature plasma conditions [1]. This merging of ion speeds suggests that ion-ion friction may be playing a role, but standard Coulomb collisions are far too weak to explain the measurements. In this work, we discuss how the experimental results can be understood by accounting for wave-particle collisions from ion-ion two-stream instabilities. These instabilities arise when the differential flow speed between the ion species exceeds a threshold value that depends on the ion species concentrations and the electron-ion temperature ratio. When this threshold is exceeded, wave-particle interactions rapidly increase the collision rate leading to an ion-ion friction force that effectively "locks" the differential flow speed to the instability threshold. This provides a second constraint that can be used to determine the speed of each ion species at the sheath edge. We present numerical calculations of the instability threshold, and new particle-in-cell simulations that show the presence of both the instabilites and enhanced friction force. Only by accounting for the instabilites can theory predict the simulated ion speeds at the sheath edge.

*Work supported by the University of Iowa, and the USDOE Fusion Energy Sciences Postdoctoral Fellowship Program.

[1]Hershkowitz, Yip, and Severn, Phys. Plasmas **18**, 057102 (2011), and references therein.

Contributed Papers

8:30

CT1 2 Ion Energy and Angular Distribution Functions at the Material Wall of a Magnetized Plasma Sheath DAVIDE CURRELI, RINAT KHAZIEV, *Nuclear, Plasma, and Radiological Engineering Department, University of Illinois at Urbana Champaign, USA* We present a calculation of the ion energy distribution and the ion angular distribution at the material wall of a magnetized plasma sheath. The calculation has been done using two different techniques: a Monte-Carlo method, propagating the trajectories of a Maxwellian population of ions across the ExB field of the magnetized sheath, and a Particle-in-Cell, giving a self-consistent treatment of the plasma behavior from the quasi-neutral region to the material boundary. Data are presented for magnetic fields inclined at angles from 0.0 to 88 degrees with respect to the normal to the surface, and field magnitudes up to 1.0 Tesla. The plasma sheath accelerates the ions up to energies scaled with the electron temperature. The ion angular distributions exhibit surprising non-linear trends, depending on both the plasma conditions and magnetic field. Ions can hit the wall at angles close to the surface normal with single-lobe IADF's, or at grazing angles with double-lobe IADF's. The energy-angle distributions strongly affect the material response, comprising electron secondary emission and material sputtering.

8:45

CT1 3 Analytical model of plasma sheaths at intermediate radio frequencies MARK SOBOLEWSKI, *National Institute of Standards and Technology* Analytical models of plasma sheaths provide physical insight and are useful in 2-d and 3-d plasma simulations, where numerical solution of the sheath equations at each boundary point is impractical. Analytical models have long been known for the high-frequency and low-frequency limits, where the ion transit time is either much greater than or much less than the rf period. At intermediate frequencies, however, sheath behavior is more complicated. In addition to the well-known narrowing of ion energy distributions (IEDs) there are other, lesser known effects, including changes in the ion current (which becomes strongly time-dependent within the sheath) and in IED peak intensities, average ion energy, sheath impedance, and sheath power. Here, we describe a new approach for modeling intermediate-frequency, collisionless sheaths. It captures the essential elements of ion dynamics yet still provides analytical expressions for most sheath properties. Predictions of the analytical model are compared to previous analytical models, numerical models, and, where possible, experimental data. The model yields new insights into ion dynamics and may serve to increase the accuracy of plasma simulations, particularly their predictions for average ion energy and power.

9:00

CT1 4 Size dependent transitions induced by an electron collecting electrode near the plasma potential* EDWARD BARNAT, GEORGE LAITY, MATT HOPKINS, *Sandia National Laboratories* SCOTT BAALRUD, *Department of Physics and Astronomy, University of Iowa* As the size of a positively biased electrode increases, the nature of the interface formed between the electrode and the host plasma undergoes a transition from an electron-rich structure (electron sheath) to an intermediate structure containing both ion and electron rich regions (double layer) and ultimately forms an electron-depleted structure (ion sheath). In this study, measurements are performed to further test how the key scaling relationship relating the area of the electrode to that of the area of the vessel containing the plasma discharge impacts this transition. This was accomplished using a segmented disk electrode in which individual segments were individually biased to change the effective surface area of the anode. Measurements on bulk plasma parameters such as the collected current density, plasma potential, electron density, electron temperature and optical emission are made as both the size and the bias placed on the electrode are varied. Size dependent transitions in the voltage dependence of the plasma parameters are identified in both argon and helium discharges and are compared to the interface transitions predicted by global current balance [1].

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

[1]S. D. Baalrud, N. Hershkowitz, and B. Longmier, Phys. Plasmas **14**, 042109 (2007).

9:15
CT1 5 Sheath structure transition controlled by secondary electron emission at low gas pressure IRINA SCHWEIGERT, *George Washington University Washington, D.C. 20052 USA* SAMUEL J. LANGENDORF, *Georgia Institute of Technology Atlanta, GA 30332 USA* MICHAEL KEIDAR, *George Washington University Washington, D.C. 20052 USA* MITCHELL L.R. WALKER, *Georgia Institute of Technology Atlanta, GA 30332 USA* Previously the experiments [1] demonstrated that the growth of the electron temperature with power in the Hall thruster is restricted by plasma-wall interaction if the wall has an enhanced secondary electron emission (SEE) yield. It is known that the plasma and wall is separated by the sheath potential drop to provide the condition of zero-current on the surface with floating potential. The rearrangement of the sheath structure near the plate with enhanced SEE is the subject of our experimental and theoretical study. The experiment was carried out in multidipole plasma device, where plasma is maintained by the negatively-biased emissive filament. The plate with sapphire surface is placed 50 cm apart from the filament. The plasma parameters were measured for different negative biases U_b and discharge currents J at $P = 10^{-4}$ Torr. In our PIC simulations the plasma was calculated for the experimental conditions. We solved self-consistently the Boltzmann equations for the electron and ion distribution functions and Poisson equation for electrical field. Both in the experiment and simulation we found non-monotonic change in sheath structure near the plate depending on U_b and J. The kinetic simulations allowed us to describe the sheath rearrangement in terms of the electron energy distribution function.

[1]Y. Raitses *et al.*, Phys. Plasmas **13**, 014502 (2006).

SESSION CT2: PROPULSION AND AERODYNAMICS
Tuesday Morning, 4 November 2014
Room: State C at 8:00

Contributed Papers

8:00
CT2 1 Using the DC self-bias effect for simultaneous ion-electron beam generation in space thruster applications* DMYTRO RAFALSKYI, ANE AANESLAND, *Laboratoire de Physique des Plasmas (CNRS, Ecole Polytechnique, Sorbonne Universités, UPMC Univ Paris 06, Univ Paris-Sud), Ecole Polytechnique* In this work we discuss ways to use the self-bias effect for broad ion-electron beam generation and present recent experimental results. In asymmetrical systems the self-bias effect leads to rectification of the applied RF voltage to a DC voltage dropped across the space charge sheath near to the electrode having smaller area. Thus, continuous ion acceleration is possible towards the smaller electrode with periodical electron extraction due to the RF plasma potential oscillations. We propose a new concept of neutralizer-free gridded space thruster called NEPTUNE. In this concept, the RF electrodes in contact with the plasma are replaced by a two-grid system such that "the smaller electrode" is now the external grid. The grids are biased with RF power across a capacitor. This allows to locate RF space charge sheath between the acceleration grids while still keeping the possibility of a DC self-bias generation. Here we present first proof-of-concept of the NEPTUNE thruster prototype and give basic parameters spacing for such thruster. Comparison of the main parameters of the beam generated using RF and a classical "DC with neutralizer" acceleration method shows several advantages of the NEPTUNE concept.

*This work was supported by a Marie Curie International Incoming Fellowships within the 7th European Community Framework (NEPTUNE PIIF-GA-2012-326054).

8:15
CT2 2 Experimental Study of RailPAc Plasma Actuator for High-Authority Aerodynamic Flow Control in One Atmosphere MILES GRAY, YOUNG-JOON CHOI, LAXMINARAYAN RAJA, JAYANT SIROHI, *University of Texas at Austin* Dielectric barrier discharge (DBD) actuators, a type of electrohydrodynamic (EHD) plasma actuator, have generated considerable interest in recent years. However, theoretical performance limitations hinder their application for high speed flows [1]. Magnetohydrodynamic (MHD) plasma actuators with higher control authority circumvent these limitations, offering an excellent alternative. The rail plasma actuator (RailPAc) is an MHD actuator which uses Lorentz force to impart momentum to the surrounding air [2]. RailPAc functions by generating a fast propagating arc column between two rail electrodes that accelerate the arc through $J \times B$ forces in a self-induced B-field. The arc column drags the surrounding air to induce aerodynamic flow motion. Our study of the RailPAc will include a description of the transient arc discharge structure through high-speed imaging and a description of the arc composition and temperature through time-resolved emission spectroscopy. Time-resolved force measurements quantify momentum transfer from the arc to the surrounding air and provides a direct measure of the actuator control authority.

[1]D. F. Opaits *et al.*, J. Appl. Phys. **104**, 043304.
[2]B. Pafford *et al.*, J. Appl. Phys. D **46**, 485208.

Invited Papers

8:30
CT2 3 Enhanced momentum delivery by electric force to an ion flux due to collisions of ions with neutrals*
AMNON FRUCHTMAN, *H.I.T.-Holon Institute of Technology*

A major figure of merit in propulsion in general and in electric propulsion in particular is the thrust per unit of deposited power, the ratio of thrust over power. We have recently demonstrated experimentally and theoretically [1–4] that for a fixed deposited power in the ions, the momentum delivered by the electric force is larger if the accelerated ions collide with neutrals during the acceleration. The higher thrust for given power is achieved for a collisional plasma at the expense of a lower thrust per unit mass flow rate, reflecting what is true in general, that the lower the flow velocity is, the higher the thrust for a given power. This is the usual trade-off between having a large specific impulse and a large thrust. Broadening the range of jet velocities and thrust levels is desirable since there are different propulsion requirements for different space missions. The mechanism of thrust enhancement by ion-neutral collisions has been investigated in the past in the case of electric pressure, what is called ionic wind [5]. I will describe in the talk experimental results for an enhanced thrust due to ion-neutral collisions in a configuration where the thrust is a result of magnetic pressure [1,3]. The plasma is accelerated by $\vec{J} \times \vec{B}$ force, in a configuration similar to that of Hall thrusters. Our measurements for three different gases and for various gas flow rates and magnetic field intensities, confirmed that the thrust increase is proportional to the square-root of the number of ion-neutral collisions [3]. Additional measurements of local discharge parameters will be shown to be consistent with the force measurements. Issues that are crucial for the use of this mechanism in an electric thruster will also be discussed. These are the possible increase of the electron transport across magnetic field lines by electron-neutral collisions, and the possible effect on various sources of inefficiency.

*Supported by Grant No. 765/11 from the Israel Science Foundation.

[1]G. Makrinich and A. Fruchtman, Phys. Plasmas **16**, 043507 (2009); Appl. Phys. Lett. **95**, 181504 (2009).
[2]A. Fruchtman, IEEE Trans. Plasma Sci. **39**, 530 (2011).
[3]G. Makrinich and A. Fruchtman, Phys. Plasmas **20**, 043509 (2013).
[4]A. Fruchtman, Plasma Chem. Plasma Process **34**, 647 (2014).
[5]R. S. Sigmond, J. Appl. Phys. **53**, 891 (1982).

Contributed Papers

9:00

CT2 4 Optical Diagnostics of Air Flows Induced in Surface Dielectric Barrier Discharge Plasma Actuator TAKUYA KOBATAKE, MASANORI DEGUCHI, JUNYA SUZUKI, KOJI ERIGUCHI, KOUICHI ONO, *Kyoto University* A surface dielectric barrier discharge (SDBD) plasma actuator has recently been intensively studied for the flow control over airfoils and turbine blades in the fields of aerospace and aeromechanics. It consists of two electrodes placed on both sides of the dielectric, where one is a top powered electrode exposed to the air, and the other is a bottom grounded electrode encapsulated with an insulator. The unidirectional gas flow along the dielectric surfaces is induced by the electrohydrodynamic (EHD) body force. It is known that the thinner the exposed electrode, the greater the momentum transfer to the air is [1], indicating that the thickness of the plasma is important. To analyze plasma profiles and air flows induced in the SDBD plasma actuator, we performed time-resolved and -integrated optical emission and schlieren imaging of the side view of the SDBD plasma actuator in atmospheric air. We applied a high voltage bipolar pulse (4–8 kV, 1–10 kHz) between electrodes. Experimental results indicated that the spatial extent of the plasma is much smaller than that of the induced flows. Experimental results further indicated that in the positive-going phase, a thin and long plasma is generated, where the optical emission is weak and uniform; on the other hand, in the negative-going phase, a thick and short plasma is generated, where a strong optical emission is observed near the top electrode.

[1]C. L. Enloe *et al.*, AIAA J. **42**, 595604 (2004).

9:15

CT2 5 Time-Resolved Laser-Induced Fluorescence Measurements of Ion Velocity Distribution in the Plume of a 6 kW Hall Thruster with Unperturbed Discharge Oscillations CHRISTOPHER DUROT, ALEC GALLIMORE, *University of Michigan* We present laser-induced fluorescence (LIF) measurements of the time-resolved ion velocity distribution in the plume of a 6 kW laboratory Hall thruster. To our knowledge, these are the first measurements of time-resolved ion velocity distribution on completely unperturbed Hall thruster operating conditions. To date, time-resolved LIF measurements have been made on Hall thrusters with oscillations driven or perturbed to be amenable to averaging techniques that assume a periodic oscillation. Natural Hall thruster breathing and spoke oscillations, however, are not periodic due to chaotic variations in amplitude and frequency. Although the system averages over many periods of nonperiodic oscillation, it recovers the time-resolved signal in part by assuming that a constant transfer function exists relating discharge current and LIF signal and averaging over the transfer function itself (http://dx.doi.org/10.1063/1.4856635). The assumption of a constant transfer function has been validated for a Hall thruster and the technique is now applied to a Hall thruster for the first time.

Invited Papers

9:30

CT2 6 The physics, performance and predictions of the PEGASES ion-ion thruster*
ANE AANESLAND, *LPP - Ecole Polytechnique*

Electric propulsion (EP) is now used systematically in space applications (due to the fuel and lifetime economy) to the extent that EP is now recognized as the next generation space technology. The uses of EP systems have though been limited to attitude control of GEO-stationary satellites and scientific missions. Now, the community envisages the use of EP for a variety of other applications as well; such as orbit transfer maneuvers, satellites in low altitudes, space debris removal, cube-sat control, challenging scientific missions close to and far from earth etc. For this we need a platform of EP systems providing much more variety in performance than what classical Hall and Gridded thrusters can provide alone. PEGASES is a gridded thruster that can be an alternative for some new applications in space, in particular for space debris removal. Unlike classical ion thrusters, here positive and negative ions are alternately accelerated to produce thrust. In this presentation we will look at the fundamental aspects of PEGASES. The emphasis will be put on our current understanding, obtained via analytical models, PIC simulations and experimental measurements, of the alternate extraction and acceleration process. We show that at low grid bias frequencies (10 s of kHz), the system can be described as a sequence of negative and positive ions accelerated as packets within a classical DC mode. Here secondary electrons created in the downstream chamber play an important role in the beam space charge compensation. At higher frequencies (100 s of kHz) the transit time of the ions in the grid gap becomes comparable to the bias period, leading to an "AC acceleration mode." Here the beam is fully space charge compensated and the ion energy and current are functions of the applied frequency and waveform. A generalization of the Child-Langmuir space charge limited law is developed for pulsed voltages and allows evaluating the optimal parameter space and performance of PEGASES.

*This work received financial state aid managed by the Agence Nationale de la Recherche under the reference ANR-2011-BS09-40 (EPIC) and ANR-11-IDEX-0004-02 (Plas@Par).

SESSION CT3: PLASMA CHEMISTRY
Tuesday Morning, 4 November 2014
Room: State D at 8:00
Igor Adamovich, Non-Equilibrium Thermodynamics Laboratory, the Ohio State University, presiding

Contributed Papers

8:00

CT3 1 Measurements of Nitric Oxide in a Plasma Generated by a Variable-Width, Constant Energy Discharge DAVID BURNETTE, IGOR ADAMOVICH, WALTER LEMPERT, *The Ohio State University* NON-EQUILIBRIUM THERMODYNAMICS LABORATORY TEAM A diffuse plasma filament within a low pressure sphere gap was generated using a high voltage, solid state switch. For a constant pressure and overvoltage, the peak current and voltage drop were altered by a change in the ballast resistor while a simultaneous adjustment to the variable pulse width was used to maintain a constant pulse energy. The discharge parameters were chosen to result in a quasi-steady state discharge with near constant current and very little change in size and uniformity for each condition studied. The absolute density and temporal evolution of nitric oxide (NO) was measured via laser-induced fluorescence for each condition. The effect of the pulse characteristics and estimated E/N on the formation of NO are discussed.

8:15

CT3 2 Characterization of Atmospheric Pressure Carbon Dioxide Dissociation in Arrays of Microplasma Channels by Emission Spectroscopy and Effluent Analysis* ZHEN DAI, CHUL SHIN, SUNG-JIN PARK, JAMES GARY EDEN, *University of Illinois at Urbana-Champaign* Levied by rigorous regulations, the enormous cost of atmospheric carbon dioxide emission urged voracious demands on remediation technologies globally. Microplasma technology is being investigated as a new candidate to efficiently dissociate or remediate carbon dioxide contained in atmosphere. At a flow rate of 60 sccm of pure CO_2 feedstock gas, dissociation degree of up to 14% has been achieved with stable glow discharges in an array of Al/Al_2O_3 microplasma channels. In-situ characterizations of the effluent gases were conducted with residual gas analysis, gas chromatography, and infrared spectroscopy. Furthermore, time and spatially resolved emission spectroscopy recorded with an intensified charge-coupled device in the 300-800 nm region revealed the excitation of CO and C_2 species. The implications on the possible plasma chemistry and its reaction mechanisms in the microdischarge will be discussed.

*Work supported by AFOSR.

8:30

CT3 3 Plasma activated dissociation of CO_2 studied in a dielectric barrier discharge RICHARD ENGELN, *Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands* FLORIAN BREHMER, *AFS GmbH, Von-Holzapfel-Straße 10, 86497 Horgau, Germany* STEFAN WELZEL, *Dutch Institute for Fundamental Energy Research, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands* BART KLARENAAR, *Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands* RICHARD VAN DE SANDEN, *Dutch Institute for Fundamental Energy Research, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands* TU/E COLLABORATION, AFS GMBH COLLABORATION, DIFFER COLLABORATION The ever-increasing emission of carbon dioxide into the atmosphere as well as the intermittency problem of electricity produced by renewable energy sources are challenges that urgently need to be addressed. An approach addressing both issues at the same time is converting CO_2 to a fuel using plasma driven by electricity from renewable sources. We will present in this contribution the results of a study on the conversion of CO_2 to CO in a dielectric barrier discharge in pure CO_2 at pressures up to 1000 mbar: FTIR absorption and Raman spectroscopy were applied to measure CO number densities and gas temperatures as function of the specific injected energy. CO densities with a maximum at 10^{18} cm^{-3} (mixing ratio of 4.4%) at 46 kJ/sl, energy efficiencies in the range of a few percent and gas temperatures up to 550 K were detected. The CO production is directly linked with the total number of transferred charges q during the residence time t_{res} of CO_2 molecules. Also ozone has been detected with a maximum mixing ratio of 0.075%.

8:45

CT3 4 Core and afterglow plasma chemistry of a kHz-driven atmospheric-pressure plasma jet operated in ambient air TOMOYUKI MURAKAMI, *Tokyo Institute of Technology* KARI NIEMI, TIMO GANS, DEBORAH O'CONNELL, *University of York* WILLIAM GRAHAM, *Queens University Belfast* When atmospheric-pressure plasma jets (APPJs) are operated under an open-air condition, the plasma tends to produce numerous reactive species and the plasma-induced chemical reactions are complex. The purpose of this paper is to quantify the relevant reactive species, e.g. RONS, HxOy, NOx and HNOx, and to analyse their formation in the core and afterglow regions of helium-based kHz-driven

APPJ by using a 0D time-dependent global simulation (comprising 1360 elementary reactions among 65 species) [1] as well as to compare the predictions with independent diagnostics. The interacting kinetics of long-lived and short-lived species is clarified. The metastable species, e.g. He* and He2*, positive ions, negative ions and electrons are strongly modulated at the driving frequency, while the most neutral reactive species are not. Those responses are influenced by the humid air fraction.

[1]T. Murakami et al., Plasma Sources Sci. Technol. **22**, 015003 (2013); **23**, 025005 (2014).

9:00

CT3 5 On the Role of Metastable Argon in Cold Atmospheric Pressure Plasma Jets with Shielding Gas Device* ANSGAR SCHMIDT-BLEKER, JORN WINTER, *ZIK plasmatis at the INP Greifswald e.V.* JOAO SANTOS SOUSA, VINCENT PUECH, *Laboratoire de Physique des Gaz et des Plasmas (LPGP), CNRS & Université Paris-Sud* KLAUS-DIETER WELTMANN, STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* ZIK PLASMATIS AT THE INP GREIFSWALD E.V. TEAM, LABORATOIRE DE PHYSIQUE DES GAZ ET DES PLASMAS (LPGP), CNRS & UNIVERSITÉ PARIS-SUD TEAM Shielding gas devices are a valuable tool for controlling the reactive species output of Cold Atmospheric Pressure Plasma (CAPP) Jets for biomedical applications. In this work we investigate the effect of different shielding gas compositions using a CAPP jet (kinpen) operated with argon. As shielding gas various mixtures of N_2 and O_2 are used. Metastable argon (Ar^*) has been quantified using laser absorption spectroscopy and was identified as an important energy carrier in the CAPP jets effluent. The Ar^* excitation dynamics was studied using phase resolve optical emission spectroscopy. Based on these findings a kinetic model for the gas phase chemistry has been developed that uses the Ar^* density and dynamics as input and yields densities of O_3, NO_2, HNO_2, HNO_3, N_2O_5, H_2O_2 and N_2O produced by the CAPP jet for different shielding gas compositions. The results are in good agreement with Fourier-Transform Infrared Spectroscopy measurements on these species.

*Authors gratefully acknowledge the funding by German Federal Ministry of Education a Research (BMBF) (Grant # 03Z2DN12).

SESSION DT1: PLASMA DIAGNOSTICS I
Tuesday Morning, 4 November 2014
Room: State EF at 10:00
Jean-Paul Booth, Ecole Polytechnique, presiding

Contributed Papers

10:00

DT1 1 Surface wave discharge in helium: evolution of metastable density and temperatures with operating parameters AHMAD HAMDAN, JOELLE MARGOT, *University of Montreal* FRANÇOIS VIDAL, *INRS* PLASMA PHYSICS TEAM, EMT TEAM Metastable and resonant-state atoms play an important role in the kinetics of gas discharges (e.g. stepwise ionization and excitation processes). In this contribution, we study a surface-wave discharge in helium. Properties of the plasma such as metastable density, gas temperature and excitation temperature were studied as a function of the operating parameters (pressure, power and axial position z). Rotational temperatures of OH, NH and N_2^+ (impurities) are estimated by fitting the experimental rotational spectra by synthetic spectra. It was observed that the rotational temperature of N_2^+ is far to be in thermal equilibrium with the gas. The temperature of the latter T_g is better described by the rotational temperature of the OH radical. Its evolution was studied as a function of z, power and pressure. T_g was found to change from 400 to 1000 K, depending of discharge conditions. The excitation temperature was estimated to be about 0.55 eV using the Bolzmann plot method. The corresponding electron temperature and density were assumed to be 3–4 eV and 1–4 10^{12} /cm^3, respectively, based on the results of collisional-radiative models presented in literature. The metastable density n^* in the 2^3S level was determined using absorption spectroscopy. It was observed that n^* depends neither of the power nor of the axial position. However, an important dependence of the pressure was observed. n^* decreases from 10^{11} to 10^{10}/cm^3 when the pressure increases from 5 to 50 Torr.

10:15

DT1 2 Spectroscopic Examination of Vibrational and Rotational Properties of NO $A^2\Sigma^+$ Metastable State from NO γ-Band Spectra in N_2-O_2 Mixture Microwave Discharge HAO TAN, ATSUSHI NEZU, HARUAKI MATSUURA, HIROSHI AKATSUKA, *Tokyo Institute of Technology* The spectra are observed in our microwave discharge plasma experiments. N_2-O_2 mixture plasma is generated by using a rectangular waveguide. We measured the spectra at 0, 60, 100 and 140 mm with the discharge pressure several Torrs. From these results, we can find that both NO and N_2 molecules experience a cooling down process both on vibrational and rotational temperatures as the plasma flows to the downstream direction. And NO molecule has always a higher rotational temperature than N_2. Meanwhile, we can see that in this nonequilibrium plasma, both NO and N_2 molecules tend to get higher energy for vibrational motion than for rotational motion. We also change the gas partial pressure rate, when O_2 molar ratio of the mixture increases, the NO experiences an increasing vibrational temperature. This is because that the NO $A^2\Sigma^+$ metastable state is excited from two main paths: $N_2(A\ ^3\Sigma_u^+)$+NO$(X\ ^2\Pi)$ $\rightarrow$ $N_2(X\ ^1\Sigma_g^+)$+NO$(A\ ^2\Sigma^+)$, (1) NO$(X\ ^2\Pi)$+e^- $\rightarrow$ NO$(A\ ^2\Sigma^+)$+e^- (2) When O_2 or N_2 is the majority of the discharge species, reaction (2) or (1) dominates the excitation process of NO $A^2\Sigma^+$, respectively. Therefore, under our plasma conditions, vibration-vibration energy transition of the reaction (1) results in a strong vibrational relaxation of NO $A^2\Sigma^+$ state molecules when N_2 is the majority in the discharge gas. In conclusion, the admixture of N_2 gas can lead to the reduction of average vibrational temperature significantly.

10:30

DT1 3 Diagnostics of Pulsed Hydrogen Plasmas JEROME DUBOIS, GILLES CUNGE, OLIVIER JOUBERT, MAXIME DARNON, LAURENT VALLIER, *Univ. Grenoble Alpes, CNRS, CEA-Leti, LTM, F-38000 Grenoble, France* NICOLAS POSSEME, *CEA, LETI, MINATEC Campus, F-38054 Grenoble, France* ETCHING GROUP TEAM Hydrogen plasmas present a great potential interest for new materials such as graphene or C-nanotubes. To modify or clean such ultrathin layers without damaging the material, low ion energy bombardment is required (conditions such as those obtained in pulsed ICP reactor). By contrast, for other applications the ion energy must be high, to get a significant etch rate for example. To assist the development of innovative processes in H2 plasmas, we have thus analyzed systematically CW and pulsed H2 plasmas both with and without RF bias power. In particular, we carry out time-resolved ion flux, and time-averaged ion energy measurements in different pulsing configurations. A large variety of ion energies and shapes of IVDF are reported depending on pulsing parameters. The IVDF are typically very broad (due to the low ion transit time of low mass ion through the sheath) and either bi or tri-modal (H+, H2+ and H3+ contributions). The time variations of the ion flux in pulsed plasmas also presents peculiar features that will be discussed. Finally, we show that a specific issue is associated to H2 plasmas: they reduce the chamber walls material therefore releasing impurities (O atoms. . .) in the plasma with important consequences on processes.

10:45

DT1 4 Characterization of a Diverging Cusped Field Thruster Operating on Krypton NATALIA MACDONALD-TENENBAUM, *Air Force Research Laboratory* LANDON TANGO, *ERC, Inc.* WILLIAM HARGUS, JR., *Air Force Research Laboratory* MICHAEL NAKLES, *ERC, Inc.* The Diverging Cusped Field Thruster (DCFT) is a low-power plasma with a cusped magnetic field profile. The magnetic fields have strong gradients that cause energetic electrons to mirror back and forth within the discharge chamber, enhancing propellant ionization. Radial portions of the magnetic field are seen only at magnet interfaces, thereby mitigating the ion impingement and heat flux to the channel walls that reduces thruster lifetime. The DCFT has been studied extensively while operating on xenon. This work represents the initial efforts at characterizing the DCFT operating on krypton. Krypton has gained interest in recent years as an alternate propellant for plasma propulsion, mainly because its lower cost has the potential to provide great savings for satellite missions. The results presented include a mapping of changes in the DCFT's discharge current with varying applied anode voltages and propellant mass flow rates, and frequency analysis of the discharge current oscillations. Additionally, time-averaged and time-synchronized laser induced fluorescence velocimetry are used to examine the ionization and acceleration regions of the discharge channel in an effort to better understand the dynamics of the thruster operation on krypton.

Invited Papers

11:00

DT1 5 Optical emission spectroscopy at different timescales: nanoseconds, microseconds, milliseconds*
JOHN B. BOFFARD, *University of Wisconsin-Madison*

Analysis of plasma optical emissions can provide a simple, non-invasive way of measuring key plasma parameters such as the electron temperature and electron density. Due to the short radiative lifetimes of excited states, the plasma emissions can be used to track the near-instantaneous state of time-varying plasmas. Using a small set of argon emission lines along with a low-resolution spectrometer we have monitored the effective electron temperature, electron density, and number densities of long-lived excited Ar($3p^5 4s$) atoms in near real-time (update rate 10 Hz, T=100 ms) for an inductively-coupled plasma (ICP) under a wide variety of plasma conditions [1]. When this same set of Ar emission lines are measured with a faster time-response by using a monochromator/PMT, the plasma conditions on a microsecond timescale can be monitored in pulsed plasmas. Time-resolved measurements of neon emission lines at an even higher time resolution (~ 5 ns) have been used as a probe for the presence of high energy electrons which occur during only select portions of the 13.56 MHz rf cycle in Ne/Ar ICP discharges [2].

*This work was supported by NSF Grants CBET 0714600 and PHY-1068670.

[1]J. Vac. Sci. Technol. A **31**, 021303 (2013).
[2]J. Phys. D: Appl. Phys. **45**, 382001 (2012).

SESSION DT2: PLASMA MODELING AND SIMULATIONS I
Tuesday Morning, 4 November 2014
Room: State C at 10:00
Miles Turner, National Center for Plasma Science Technology, Dublin City University, presiding

Contributed Papers

10:00

DT2 1 Numerical Simulations for ICP Source for Implant Applications VLADIMIR KUDRIAVTSEV, BABAK ADIBI, TERRY BLUCK, *Intevac, Santa Clara, CA* VLADIMIR KOLOBOV, *CFDRC, Huntsville, Al* ICP Plasma source characteristics depend significantly on cavity aspect ratio and operating pressure [1]. In this work we investigate the effect of chamber height and antenna coil placement on current flux and plasma uniformity at pressures in 5 mtorr – 1torr range and also study computationally appropriate scaling laws. Cavity dimensions are 0.2×0.2 m. CFD-ACE/Plasma software is used to conduct 2D planar plasma simulations for Ar and H2 plasmas. Software allows use of unstructured and non-uniform mesh to resolve geometry details. At low pressure plasma peaks in the middle of the cavity even when RF antenna is placed on top. Results show that there is a maximum in plasma density that corresponds with a unique aspect ratio.

[1]C. Biloiu *et al.*, US Patent 8,590,485B2.

10:15

DT2 2 Hybrid Global Model Simulations of He/N_2 and He/H_2O Atmospheric Pressure Capacitive Discharges* M.A. LIEBERMAN, E. KAWAMURA, *Univ of California-Berkeley* DING KE, *Donghua Univ-China* A.J. LICHTENBERG, *Univ of California-Berkeley* P. CHABERT, *Ecole Polytechnique-France* C. LAZZARONI, *Universite Paris 13 France* We used 1D particle-in-cell (PIC) simulations of an atmospheric He/0.1%N_2 discharge with simplified chemistry to guide the development of a hybrid analytical/numerical global model that includes electron multiplication and two classes of electrons: "hot" electrons associated with the sheaths, and "warm" electrons associated with the bulk. The model and PIC results show reasonable agreement and indicate a transition from a low power α-mode with a relatively high bulk electron temperature T_e to a high power γ-mode with a low T_e. The transition is accompanied by an increase in density and a decrease in sheath widths. Water is a trace gas of bio-medical interest since it may arise from contact with skin. We use the hybrid global model to simulate a chemically complex, bounded He/H_2O atmospheric pressure discharge, including 148 volume reactions among 43 species, and including clusters up to $H_{19}O_9^+$. For a planar discharge with a 1 cm electrode radius and a 0.5 mm gap driven at 13.56 MHz, we determine the depletion and diffusion effects and the α to γ transition for secondary emission $\gamma_{se} = 0.25$ over a range of rf currents and external H_2O concentrations. Each simulation takes about 2 minutes on a moderate laptop.

*This work was partially supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC000193 and by the Natural Science Foundation of China Contract 11375042.

10:30

DT2 3 The effect of including fast neutrals and energy-dependent γ-coefficients in PIC simulations of capacitive RF plasmas JULIAN SCHULZE, *Department of Physics, West Virginia University* ARANKA DERZSI, IHOR KOROLOV, ZOLTAN DONKO, *Hungarian Academy of Sciences* EDMUND SCHUENGEL, *Department of Physics, West Virginia University* In most PIC simulations of capacitive RF plasmas operated in noble gases only electrons and ions are traced and a constant ion induced secondary electron emission coefficient of $\gamma_{ion} \approx 0.1$ is used. Here, we demonstrate that tracing fast neutrals that originate from elastic ion-atom collisions in the sheaths, including ionization as well as secondary electron emission induced by these particles, and implementing realistic energy dependent γ-coefficients are essential for obtaining realistic results from such simulations. We find that the ionization caused by fast neutrals strongly enhances the plasma density in simulations of argon discharges driven at 13.56 MHz. This leads to smaller sheaths and limits the maximum driving voltage amplitudes, at which the simulation converges. Both effects are in agreement with experimental findings. Including realistic γ-coefficients also affects the plasma density and other process relevant parameters such as the ion energy and flux at the electrodes. The correct implementation of the energy dependence of secondary electron emission is found to have a drastic effect, if global control parameters used to change the ion bombardment energy in applications are tuned.

10:45

DT2 4 Modeling Argon Plasma Excimer Characteristics near a Dielectric Surface in Miniaturized Volumes* ASHRAF FARAHAT, *College of Applied and Supporting Studies, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia* EMAD RAMADAN, *Department of Information and Computer Science, King Fahd University of Petroleum and Minerals, Dhahran 31261 Saudi Arabia* We computationally model plasma -neutral gas dynamics in a miniaturized microthruster encloses Ar and contains a dielectric material sandwiched between two metal plates using a two dimensional plasma model. Spatial and temporal plasma properties are investigated by solving the Poisson equation with the conservation equations of charged and excited neutral plasma species. We find the microthruster properties to depend on small changes in the secondary electron emission coefficient that could result from dielectric erosion and aging. The changes also affect the electrohydrodynamic force produced when we use the microthruster to generate thrust for small spacecrafts. The electrohydrodynamic force is calculated and found to be significant in the sheath area near the dielectric layer and is found to affect gas flow dynamics including the Ar excimer formation and density. The plasma-neutral gas momentum exchange is significant in affecting gas flow dynamics and in the formation of excimer species in addition to affecting the UV and visible emission characteristics of the device.

*The authors would like to acknowledge the support provided by the Deanship of Scientific Research (DSR) at the King Fahd University of Petroleum & Minerals (KFUPM) for funding this work through Project No. IN111026.

11:00

DT2 5 Study of whole channel discharge characteristics of Hall Thruster under different voltages DUAN PING, *Dalian Maritime University* We used the method of Particle-in-Cell to stimulate the distribution of electron density, ion density and electron temperature with different discharge voltages in a Hall thruster channel. The variation of specific impulse with the discharge voltage was also discussed. It was found that maximum electron and ion densities are gained at the axial 15mm when the discharge voltage is ranging from 250V to 650V and the electron temperature peak emerges near the channel outlet of small axial distance. Under the condition of 700V or higher discharge voltages, highest electron temperature expands in the axial direction and the maximum densities are located in the anode vicinity where the ionization region is limited to. It also revealed that specific impulse increases with the increase of discharge voltage.

11:15

DT2 6 A Hybrid PIC/DSMC Model of Breakdown in Triggered Vacuum Spark Gaps STAN G. MOORE, CHRISTOPHER H. MOORE, JEREMIAH J. BOERNER, *Sandia National Laboratories* Triggered vacuum spark gaps (TVSGs) can be used as high voltage, high current switches with a fast switching time and a variable operating voltage, such as in pulsed power applications and crowbar circuits that protect against overvoltage conditions. Hybrid particle-in-cell (PIC) [1] and direct simulation Monte Carlo (DSMC) [2] methods can be used to simulate breakdown in TVSGs. In this talk, we present results of a one-dimensional hybrid PIC/DSMC model and show that changing the density and velocity of injected neutral particles (which can be related to the surface temperature) significantly changes both the time to breakdown and the existence of a short-lived starvation mode in the current waveform. 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).

11:30

DT2 7 Testing fluid models of different order on streamer discharges ARAM MARKOSYAN, *University of Michigan* JANNIS TEUNISSEN, *CWI* SASHA DUJKO, *University of Belgrade* UTE EBERT, *CWI* We have compared several fluid models for streamer discharges, namely the recently developed high order fluid model [1], the classical first order model using the local field approximation and the second order fluid model using the local energy approximation with drift-diffusion approximation. Simulation results for planar negative ionization fronts with all three fluid models are presented and compared. As a reference, we use a particle-in-cell/Monte Carlo (PIC/MC) model. All tests are performed for neon and nitrogen at STP for a wide range of reduced electric fields. Our simulation results show large deviations between the models for various properties of negative planar fronts. We discuss the practical and theoretical aspects of applicability of each fluid model.

[1]Dujko et al., J. Phys. D **46**, 5202 (2013).

11:45

DT2 8 Investigating the guiding of streamers in nitrogen/oxygen mixtures with 3D simulations* JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica, The Netherlands* SANDER NIJDAM, *Eindhoven University of Technology, The Netherlands* EIICHI TAKAHASHI, *National Institute of Advanced Industrial Science and Technology, Japan* UTE EBERT, *Centrum Wiskunde & Informatica and Eindhoven University of Technology, The Netherlands* Recent experiments by S. Nijdam and E. Takahashi have demonstrated that streamers can be guided by weak pre-ionization in nitrogen/oxygen mixtures, as long as there is not too much oxygen (less than 1%). The pre-ionization was created by a laser beam, and was orders of magnitude lower than the density in a streamer channel. Here, we will study the guiding of streamers with 3D numerical simulations. First, we present simulations that can be compared with the experiments and confirm that the laser pre-ionization does not introduce space charge effects by itself. Then we investigate topics as: the conditions under which guiding can occur; how photoionization reduces the guiding at higher oxygen concentrations and whether guided streamers keep their propagation direction outside the pre-ionization.

*JT was supported by STW Project 10755, SN by the FY2012 Researcher Exchange Program between JSPS and NWO, and ET by JSPS KAKENHI Grant Number 24560249.

SESSION DT3: EFFECTS OF PLASMAS ON BIOLOGICAL CELLS

Tuesday Morning, 4 November 2014; Room: State D at 10:00; Mounir Laroussi, Old Dominion University, presiding

Invited Papers

10:00

DT3 1 Application of atmospheric plasma sources in growth and differentiation of plant and mammalian stem cells*

NEVENA PUAC, *Institute of Physics, University of Belgrade*

The expansion of the plasma medicine and its demand for in-vivo treatments resulted in fast development of various plasma devices that operate at atmospheric pressure. These sources have to fulfill all demands for application on biological samples. One of the sources that meet all the requirements needed for treatment of biological material is plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells. It is well known that plasma generates reactive oxygen species (ROS) and reactive nitrogen species (RNS) that strongly affect metabolism of living cells. One of the open issues is to correlate external plasma products (electrons, ions, RNS, ROS, photons, strong fields etc.) with the immediate internal response which triggers or induces effects in the living cell. For that purpose we have studied the kinetics of enzymes which are typical indicators of the identity of reactive species from the plasma created environment that can trigger signal transduction in the cell and ensue cell activity. In collaboration with Suzana Zivkovicm, Institute for Biological Research "Sinisa Stankovic," University of Belgrade; Nenad Selakovic, Institute of Physics, University of Belgrade; Milica Milutinovic, Jelena Boljevic, Institute for Biological Research "Sinisa Stankovic," University of Belgrade; and Gordana Malovic, Zoran Lj. Petrovic, Institute of Physics, University of Belgrade.

*Grants III41011, ON171037 and ON173024, MESTD, Serbia.

10:30

DT3 2 Minimally-Invasive Gene Transfection by Chemical and Physical Interaction of Atmospheric Pressure Plasma Flow*

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

Non-equilibrium atmospheric pressure plasma irradiated to the living-cell is investigated for medical applications such as gene transfection, which is expected to play an important role in molecular biology, gene therapy, and creation of induced pluripotent stem (iPS) cells. However, the conventional gene transfection using the plasma has some problems that the cell viability is low and the genes cannot be transferred into some specific lipid cells, which is attributed to the unknown mechanism of the gene transfection using the plasma. Therefore, the time-controlled atmospheric pressure plasma flow is generated and irradiated to the living-cell suspended solution for clarifying the transfection mechanism toward developing highly-efficient and minimally- invasive gene transfection system. In this experiment, fluorescent dye YOYO-1 is used as the simulated gene and LIVE/DEAD Stain is simultaneously used for cell viability assay. By the fluorescence image, the transfection efficiency is calculated as the ratio of the number of transferred and surviving cells to total cell count. It is clarified that the transfection efficiency is significantly increased by the short-time (<4 sec) and short-distance (<40 mm) plasma irradiation, and the high transfection efficiency of 53% is realized together with the high cell viability (>90%). This result indicates that the physical effects such as the electric field caused by the charged particles arriving at the surface of the cell membrane, and chemical effects associated with plasma-activated products in solution act synergistically to enhance the cell-membrane transport with low-damage.

*This work was supported by JSPS KAKENHI Grant Number 24108004.

Contributed Papers

11:00

DT3 3 Impact of plasma induced liquid chemistry and charge on bacteria loaded aerosol droplets* DAVID RUTHERFORD, DAVID MCDOWELL, DAVIDE MARIOTTI, CHARLES MAHONY, *University of Ulster* DECLAN DIVER, HUGH POTTS, EUAN BENNET, *University of Glasgow* PAUL MAGUIRE, *University of Ulster* The introduction of living organisms, such as bacteria, into atmospheric pressure microplasmas offers a unique opportunity to study the local chemical and electrical effects on cell structure and viability. Individual bacteria, each encapsulated in an aerosol droplet, were successfully transmitted through a non-thermal equilibrium RF coaxial plasma, using a custom-design concentric double gas shroud interface and via adjustment of transit times and plasma parameters, we can control cell viability. Plasma electrical characteristics ($n_e \sim 10^{13}$ cm^{-3}), droplet velocity profiles and aspects of plasma-induced droplet chemistry were determined in order to establish the nature of the bacteria in droplet environment. Plasma-exposed viable E coli cells were subsequently cultured and the growth rate curves (lag and exponential phase gradient) used to explore the effect of radical chemistry and electron bombardment on cell stress. The extent and nature of membrane disruption in viable and non-viable cells were investigated through genomic and protein/membrane lipid content estimation. We will also compare our results with simulations [1] of the effect of bacterial presence on plasma induced droplet charging and evaporation.

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

[1]E. Bennet *et al.*, New J. Phys. (submitted).

11:15

DT3 4 Quantitative inactivation-mechanisms of P. digitatum and A. niger spores based on atomic oxygen dose MASAFUMI ITO, *Meijo University* HIROSHI HASHIZUME, *Nagoya University* TAKAYUKI OHTA, *Meijo University* MASARU HORI, *Nagoya University* We have investigated inactivation mechanisms of Penicillium digitatum and Asperguills niger spores using atmospheric-pressure radical source quantitatively. The radical source was specially developed for supplying only neutral radicals without charged species and UV-light emissions. Reactive oxygen radical densities such as grand-state oxygen atoms, excited-state oxygen molecules and ozone were measured using VUV and UV absorption spectroscopies. The measurements and the treatments of spores were carried out in an Ar-purged chamber for eliminating the influences of OH, NOx and so on. The results revealed that the inactivation of spores can be explained by atomic-oxygen dose under the conditions employing neutral ROS irradiations. On the basis of the dose, we have observed the changes of intracellular organelles and membrane functions using TEM, SEM and confocal- laser fluorescent microscopy. From these results, we discuss the detail inactivation-mechanisms quantitatively based on atomic-oxygen dose.

11:30

DT3 5 Treatment of prostate cancer cell lines and primary cells using low temperature plasma DEBORAH O'CONNELL, ADAM HIRST, *York Plasma Institute, Department of Physics, University of York, UK* FIONA F. FRAME, NORMAN J. MAITLAND, *YCR Cancer Research Unit, Department of Biology, University of York, UK* The mechanisms of cell death after plasma treatment of both benign and cancerous prostate epithelial cells are investigated. Prostate cancer tissue was obtained with patient consent from targeted needle core biopsies following radical prostatectomy. Primary cells were cultured from cancer tissue and plated onto a chamber slide at a density of 10,000 cells per well in 200 microliter of stem cell media (SCM). The treated sample was previously identified as Gleason grade 7 cancer through tissue histo-pathology. A dielectric barrier discharge (DBD) jet configuration, with helium as a carrier gas, and 0.3% O2 admixture was used for treating the cells. Reactive oxygen and nitrogen species (RONS) produced by the plasma are believed to be the main mediators of the plasma-cell interaction and response. We found the concentration of reactive oxygen species (ROS) induced inside the cells increased with plasma exposure. Exposure to the plasma for >3 minutes showed high levels of DNA damage compared to untreated and hydrogen peroxide controls. Cell viability and cellular recovery are also investigated and will be presented. All findings were common to both cell lines, suggesting the potential of LTP therapy for both benign and malignant disease.

11:45

DT3 6 Power source effects of soft plasma jet and the differential response of skin cancer and normal cells NATHANIEL TAYLOR, *Drexel University* DANIL DOBRYNIN, *A.J. Drexel Plasma Institute* ALEXANDER FRIDMAN, *Drexel University* EUN HA CHOI, *Kwangwoon University* The effects of pulsed power direct current energy sources were compared using an indirect discharge plasma jet applied to treat cancerous and normal skin cells. Two power supplies with different voltage and current profiles were compared and optimized through the measurement of physical parameters and evaluated through the treatment of skin cells using an atmospheric pressure nitrogen gas plasma jet. Plasma density and temperature, power output, gas output temperature, and reactive species production were measured. Cell morphology, viability, and ROS generation were investigated using staining. A differential response has been shown between the normal and cancerous cell lines. The cancer cells viability reduced while normal cells did not over the same treatment time.

SESSION ET1: PLASMA DIAGNOSTICS AND SOURCES FOR BIOLOGICAL APPLICATIONS
Tuesday Afternoon, 4 November 2014
Room: State EF at 13:30
Toshiro Kaneko, Tohoku University, presiding

Contributed Papers

13:30

ET1 1 Multi-Modality Pulsed AC Source for Medical Applications of Non-Equilibrium Plasmas DANIEL FRIEDRICHS, JAMES GILBERT, *Covidien Surgical Solutions* A burgeoning field has developed around the use of non-equilibrium ("cold") plasmas for various medical applications, including wound treatment, surface sterilization, non-thermal hemostasis, and selective cell destruction. Proposed devices typically utilize pulsed DC power sources, which have no other therapeutic utility, and may encounter significant regulatory restrictions regarding their safety for use in patient care. Additionally, dedicated capital equipment is difficult for healthcare facilities to justify. In this work, we have demonstrated for the first time the generation of non-equilibrium plasma using pulsed AC output from a specially-designed electrosurgical generator. The ability to power novel non-equilibrium plasma devices from a piece of equipment already ubiquitous in operating theatres should significantly reduce the barriers to adoption of plasma devices. We demonstrate the ability of a prototype device, coupled to this source, to reduce bacterial growth in vitro. Such a system could allow a single surgical instrument to provide both non-thermal sterilization and thermal tissue dissection.

13:45

ET1 2 Selective irradiation of radicals for biomedical treatment using vacuum ultraviolet light from an excimer lamp RYO ONO, YUSUKE TOKUMITSU, SHUNGO ZEN, SEIYA YONEMORI, *The University of Tokyo* In plasma medicine, radicals are considered to play important roles. However, the medical effect of each radical, such as OH and O, is unknown. To examine the effect of each radical, selective production of radicals is needed. We developed selective production of radicals for biomedical treatment using a vacuum ultraviolet (VUV) light emitted from an excimer lamp. Selective irradiation of OH radicals can be achieved by irradiating the 172-nm VUV light from a Xe_2 excimer lamp to a humid helium flow in a quartz tube. The water molecules are strongly photodissociated by the VUV light to produce OH radicals. A photochemical simulation for the selective OH production is developed to calculate the OH density. The calculated OH density is compared with OH density measured using laser-induced fluorescence (LIF). Selective production of other radicals than OH is also discussed.

14:00

ET1 3 Diagnostic Challenges in Plasma Medicine* STEPHAN REUTER, HELENA TRESP, ANSGAR SCHMIDT-BLEKER, JOERN WINTER, SYLVAIN ISENI, MARIO DÜNNBIER, KAI MASUR, ANNEMARIE BARTON, MALTE HAMMER, *ZIK plasmatis @ INP Greifswald* THOMAS VON WOEDTKE, KLAUS-DIETER WELTMANN, *INP Greifswald* Atmospheric plasmas exhibit large gradients in space and time. This challenges diagnostics such as LIF or other quantitative species detection methods. Bringing these plasmas in contact with liquids generates further complex processes which influence reactive component generation in the plasma, gas- and liquid phase. For plasma medicine, the transfer through these phases to the cell is the task for diagnostics. In the present work, several approaches of plasma, gas and liquid diagnostics such as LIF, absorption spectroscopy, colorimetric assays or EPR spectroscopy are discussed and it is shown how a careful study of the processes can lead to an at least partial understanding of plasma interaction with biological cells.

*Support by the BMBF (FKZ 03Z2DN12) is gratefully acknowledged.

14:15

ET1 4 Measurement of OH, NO, O and N atoms in helium plasma jet for ROS/RNS controlled biomedical processes* SEIYA YONEMORI, TAKU KAMAKURA, RYO ONO, *The University of Tokyo* Atmospheric-pressure plasmas are of emerging interest for new plasma applications such as cancer treatment, cell activation and sterilization. In those biomedical processes, reactive oxygen/nitrogen species (ROS/RNS) are said that they play significant role. It is though that active species give oxidative stress and induce biomedical reactions. In this study, we measured OH, NO, O and N atoms using laser induced fluorescence (LIF) measurement and found that voltage polarity affect particular ROS. When negative high voltage was applied to the plasma jet, O atom density was tripled compared to the case of positive applied voltage. In that case, O atom density was around 3×10^{15} [cm^{-3}] at maximum. In contrast, OH and NO density did not change their density depending on the polarity of applied voltage, measured as in order of 10^{13} and 10^{14} [cm^{-3}] at maximum, respectively. From ICCD imaging measurement, it could be seen that negative high voltage enhanced secondary emission in plasma bullet propagation and it can affect the effective production of particular ROS. Since ROS/RNS dose can be a quantitative criterion to control plasma biomedical application, those measurement results is able to be applied for *in vivo* and *in vitro* plasma biomedical experiments.

*This study is supported by the Grant-in-Aid for Science Research by the Ministry of Education, Culture, Sport, Science and Technology.

14:30

ET1 5 Vacuum ultraviolet spectroscopic analysis of AC excited non-equilibrium atmospheric pressure Ar plasma jet KEIGO TAKEDA, KENJI ISHIKAWA, HIROMASA TANAKA, HIROKI KONDO, MAKOTO SEKINE, MASARU HORI, *Nagoya University* Plasma biomedical treatments with atmospheric pressure plasma jets (APPJ) have attracted very much. In the treatments, reactive species and high energy photons emitted from APPJ are important factors to realize the performance. Vacuum ultraviolet (VUV) spectroscopy is one of useful techniques to measure quantitative behaviors of atomic radicals and high energy photons. In this study, an AC excited APPJ with Ar gas has been investigated by using the spectroscopy. The Ar APPJ was generated under open air condition, and VUV emission spectra was measured by using a VUV monochromator. The spectra of atomic species such as O (130.4 nm), N (120.0, 174.3 nm), and H (121.6 nm) were observed. The emission intensity of N atom (174.3 nm) in the plasma remote region exponentially decreased with increasing the distance from the plasma jet. The absorption coefficient was estimated to be 1.8 cm^{-1}, over 20 mm distance from the plasma jet, the coefficient increase to 4.2 cm^{-1} which is almost same with value due to atmosphere. We will discuss behaviors of reactive species and high energy photons emitted from the AC excited Ar APPJ on the basis of the results measured by VUV spectroscopy.

14:45

ET1 6 Non thermal plasma jets interacting with targets and gas flows* ERIC ROBERT, T. DARNY, *GREMI/CNRS/Université d'Orléans* D. RIES, *CNRS/Université d'Orleans* S. DOZIAS, J-M. POUVESLE, *GREMI/CNRS/Université d'Orleans* Non thermal plasma jets at atmospheric pressure have been recently used in an impressive number of works including plasma diagnostics, biomedical treatments and material processing. While the plasma source setups are very simple, it has been evidenced that many parameters may significantly influence the plasma characteristics offering at the same time a large versatility for plasma delivery but also requiring a special attention to match the plasma features for any specific application. In this work, emphasis will be given on two critical topics involved in any plasma jet biomedical applications. The first consists in the influence of the target over which plasma jet impinges. It has been shown that depending on the conductivity of the target, secondary plasma generation occurs, leading to a critical modification of the reactive species generation. The second main issue concerns the strong interplay between the rare gas flow and the plasma species generated during plasma jet ionization wave propagation. Drastic modification of the rare gas flow features have been recently characterized through Schlieren visualization and ICCD imaging [1].

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

[1]E. Robert, V. Sarron, T. Darny, D. Riès, S. Dozias, J. Fontane, L. Joly, and J. M. Pouvesle, Plasma Sources Sci. Technol. **23**, 0120003 (2014).

SESSION ET2: MODELING OF PLASMA ETCHING
Tuesday Afternoon, 4 November 2014
Room: State C at 13:30
Douglas Keil, Lam Research, presiding

Contributed Papers

13:30
ET2 1 Profile Control Using Pulsed Power During Plasma Etching in Capacitively Coupled Plasmas* SANG-HEON SONG,† MARK J. KUSHNER, *University of Michigan* Profile control during plasma etching is becoming more challenging as feature sizes decrease. Pulse power in capacitively coupled plasmas (CCPs) is being developed as a means to provide more flexibility in reactive fluxes and ion energy and angular distributions (IEADs) to achieve this profile control. In this talk, we discuss results for profile control in etching of dielectrics from modeling studies of pulsed 2-frequency CCPs sustained in $Ar/CF_4/O_2$ mixtures. The simulators include a 2-d plasma hydrodynamics model to produce reactive fluxes and IEADs, and a 2-d Monte Carlo based profile model. IEADs are produced in three formats in pulsed CCPs – when both the low frequency (LF) and high frequency (HF) are on, when only the LF or HF are on, and when both the LF and HF are off. The resulting IEADs are further modified by duty cycle and the size of the blocking capacitor. We found that the side-wall slope of high-aspect-ratio (HAR) features can be controlled by combinations of pulsing the LF and/or HF, and duty cycle. In addition to the feature receiving different IEADs, the ratio of polymerizing to ion fluxes which contributes to control of sidewall slope is also sensitive to these process variables.

*Work supported by DOE Office of Fusion Energy Science, Semiconductor Research Corp. and NSF.
†Now with: Tokyo Electron Ltd., Albany, NY.

13:45
ET2 2 Insights into Plasma Etch Profile Evolution with 3D Profile Simulation SARAVANAPRIYAN SRIRAMAN, ALEX PATERSON, *Lam Research* YITING ZHANG, MARK KUSHNER, *University of Michigan* Plasma etching is critical for pattern transfer in microelectronics fabrication. For planar devices, efforts in 2D etch profile simulations were sufficient to understand critical etch process mechanisms. In contrast, to understand the complex mechanisms in etching 3D structures of current technology nodes such as FinFETs, 2D profile simulators are inadequate. In this paper, we report on development of a 3D profile simulation platform, the Monte Carlo Feature Profile Model (MCFPM-3D). The MCFPM-3D builds upon the 2D MCFPM platform that includes aspects such as mixing, implantation, and photon assisted processes and addresses reaction mechanisms in surface etching, sputtering, and deposition to predict profile evolution. Model inputs include fluxes of species from plasma derived from the Hybrid Plasma Equipment Model (HPEM). Test cases of Si/SiO_2 etching in Ar/Cl_2 and $Ar/CF_4/O_2$ plasmas for representative 2D/3D feature topographies are considered and phenomena such as selectivity and aspect ratio dependent etching will be discussed.

14:00
ET2 3 Multi Time-Step Feature Scale Simulations with FPS3D PAUL MOROZ, *Tokyo Electron U.S. Holdings, Inc.* DANIEL MOROZ, *University of Pennsylvania* Most modern materials processing recipes include many time-steps, each one utilizing different chemistry and plasma parameters, resulting in different composition of fluxes coming to the wafer and different energy and angular distributions of incoming species. The FPS3D feature scale simulator [1-2] is capable of handling varied and complex cases due to its structure and numerical techniques. For this presentation, we selected a set of simulations for processes which are dramatically different from each other. One is the Bosch process, which is a high etch-rate (in the range of 1000 A/s or more) etching for features with dimensions in the range of 1 micron to 100s of microns. The other is the ALE (atomic layer etch), in which etching is done by a single atomic layer per cycle, allowing maximal processing accuracy but with etch rate in the range of one to a few A/min. Both of these processes involve multiple cycles through the etching and passivation (or deposition) steps. FPS3D is well suited for those tasks as it allows consideration of large fluxes and large dimensions of the Bosch process as well as the delicate ALE processing on an atomic level. Results of both 2D and 3D modeling will be presented and the details of the processes will be discussed.

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

Invited Papers

14:15
ET2 4 Modeling of plasma-induced damage during the etching of ultimately-scaled transistors in ULSI circuits—A model prediction of damage in three dimensional structures*
KOJI ERIGUCHI, *Kyoto University*

An increasing demand for high performance field-effect transistors (FETs) leads to the aggressive critical dimension shrinkage and the currently-emerging three dimensional (3D) geometry [1]. Plasma processing is widely used also in the scaled- and 3D-FET (e.g. FinFET) manufacturing, where precise control of the reaction on the (sidewall) surfaces is a prime issue. In this study, damage creation mechanism during plasma etching—plasma-induced physical damage (PPD)—was investigated in such structures on the basis of the PPD range theory [2], atomistic simulations, and experiments. Compared to PPD in planar FETs (e.g. Si recess [2,3]), a stochastic modeling and atomistic simulations predicted that, during etching of "fins" in a 3D-FET, the following two mechanisms are responsible for damage creation in addition to an ion impact on the sidewall at an oblique incident angle: 1) incoming ions penetrate into the Si substrate and undergo scattering by Si atoms in the lateral direction even if the incident angle is normal to the surface [4] and 2) some of Si atoms and ions sputtered at the surface being etched impact on the sidewall with energies sufficient to break Si-Si bonds. These straggling and sputtering processes are stochastic and fundamental, thus, result in 3D structure damage ("fin-damage"). The "fin-damage" induced by straggling was modeled by the PPD range theory. Molecular dynamics simulations clarified the mechanisms under the various plasma conditions. Quantum mechanical calculations showed that created defect structures play the role of a carrier trap site, which was experimentally verified by an electrical measurement. Since they are intrinsic natures of etching, both straggling and sputtering noted here should be implemented to design a low-damage etching process.

*This work was supported in part by Grant-in-Aid for Scientific Research (B) 23360321 from JSPS and STARC project.

[1]I. Ferain *et al.*, Nature **479**, 310 (2011).
[2]K. Eriguchi *et al.*, Jpn. J. Appl. Phys. **49**, 056203 (2010).
[3]S. A. Vitale and B. A. Smith, J. Vac. Sci. Technol. B **21**, 2205 (2003).
[4]K. Eriguchi *et al.*, Jpn. J. Appl. Phys. **53**, 03DE02 (2014).

Contributed Papers

14:45

ET2 5 Molecular dynamics analysis of silicon chloride ion incidence during Si etching in Cl-based plasmas: Effects of ion incident energy, angle, and neutral radical-to-ion flux ratio NOBUYA NAKAZAKI, KOJI ERIGUCHI, KOUICHI ONO, *Kyoto University* Profile anomalies and surface roughness are critical issues to be resolved in plasma etching of nanometer-scale microelectronic devices, which in turn requires a better understanding of the effects of ion incident energy and angle on surface reaction kinetics. This paper presents a classical molecular dynamics (MD) simulation of Si(100) etching by energetic Cl_x^+ ($x = 1$–2) and $SiCl_x^+$ ($x = 0$–4) ion beams with different incident energies $E_i = 20$–500 eV and angles $\theta_i = 0$–85°, with and without low-energy neutral Cl radicals (neutral-to-ion flux ratios $\Gamma_n/\Gamma_i = 0$ and 100). An improved Stillinger-Weber interatomic potential was used for the Si/Cl system. Numerical results indicated that in Cl^+, Cl_2^+, $SiCl_3^+$, and $SiCl_4^+$ incidences for $\theta_i = 0°$ and $\Gamma_n/\Gamma_i = 0$, the etching occurs in the whole E_i range investigated; on the other hand, in $SiCl^+$ and $SiCl_2^+$ incidences, the deposition occurs at low $E_i < 300$ and 150 eV, respectively, while the etching occurs at further increased E_i [1]. For $SiCl^+$ and $SiCl_2^+$, the transition energies from deposition and etching become lowered for $\Gamma_n/\Gamma_i = 100$. Numerical results further indicated that in the $SiCl^+$ incidence for $\Gamma_n/\Gamma_i = 0$, the etching occurs in the whole θ_i range investigated for $E_i \geqslant 300$ eV; on the other hand, for $E_i = 100$ and 150 eV, the deposition occurs at low $\theta_i < 60°$ and 40°, respectively, while the etching occurs at further increased θ_i; in addition, for $E_i \leqslant 50$ eV, the deposition occurs in the whole θ_i range investigated.

[1]N. Nakazaki *et al.*, Jpn. J. Appl. Phys. **53**, 056201 (2014).

SESSION ET3: DIELECTRIC BARRIER DISCHARGES AND CORONA
Tuesday Afternoon, 4 November 2014; Room: State D at 13:30; Anne Bourdon, Ecole Polytechnique, presiding

Invited Papers

13:30

ET3 1 Recent developments in large-scale ozone generation with dielectric barrier discharges
JOSE L. LOPEZ, *Seton Hall University, Department of Physics, South Orange, NJ (USA)*

Large-scale ozone generation for industrial applications has been entirely based on the creation of microplasmas or microdischarges created using dielectric barrier discharge (DBD) reactors. Although versions of DBD generated ozone have been in continuous use for over a hundred years especially in water treatment, recent changes in environmental awareness and sustainability have lead to a surge of ozone generating facilities throughout the world. As a result of this enhanced global usage of this environmental cleaning application various new discoveries have emerged in the science and technology of ozone generation. This presentation will describe some of the most recent breakthrough developments in large-scale ozone generation while further addressing some of the current scientific and engineering challenges of this technology.

Contributed Papers

14:00

ET3 2 Ferroelectric-driven atmospheric pressure discharges MICHAEL JOHNSON, DAVID GO, *University of Notre Dame* Typically, dielectric barrier discharges (DBD) operate through a continuous cycle of charging and discharging a dielectric layer. Ferroelectrics are a subset of dielectrics that are inherently polarized due to their non-centrosymmetric crystal structure. The polarization of a ferroelectric has two or more stable conditions, and the polarization state can be switched by applying an electric field that exceeds the coercive field of the crystal. When the dielectric layer in a DBD is replaced with a ferroelectric, this change in polarization can lead to rapid changes in surface potential and be used to manipulate the charge on its surface. More so, these rapid changes in polarization of the crystal can cause strong electric fields at the surface that can lead to electron emission into the discharge. The coercive field of the ferroelectric allows for the occurrence of this emission to be controlled. Because of this, operating conditions of a ferroelectric barrier discharge can be altered to allow for discharges at lower AC voltages and with greater amounts of control. In this work, we investigate the potential advantages of using ferroelectrics crystals in place of dielectrics in a barrier discharge while investigating the effects of polarization and polarization shifting on the discharge.

14:15

ET3 3 Self-Organization in DBDs on a Single Pulse: Periodic Structures and Diffuse Discharges* NATALIA YU. BABAEVA,† MARK J. KUSHNER, *University of Michigan* Self-organization in dielectric barrier discharges (DBDs) occurs in many forms, from patterns of isolated plasma filaments to more complex arrangements. This self-organization typically develops over many discharge pulses, and is often related to charging of the dielectrics. Another aspect of DBDs is the transition from filamentary to diffuse discharges. The diffuse mode can be achieved at high repetition rate over many pulses, or on a single discharge pulse using over-voltage enabled by a fast-rising applied voltage. In computational studies of DBDs using a 2-dimensional plasma hydrodynamics model, evidence has been found for self-organized-patterns (SOPs) during a single discharge pulse. The conditions are an over-voltaged DBD sustained in humid air with two dielectric layers. We first found a transition between an isolated filament and a more diffuse discharge in raising the applied electric field to approximately 100 kV/cm. The diffuse discharge is sensitive to the surface-ionization-waves (SIWs) that propagate along both dielectrics, and the relative permittivity of those dielectrics. Upon increasing voltage further, SOPs are formed by periodic ionization waves launched into the gap from the edges of the SIWs. The gap-crossing ionization waves may be either positive or negative depending on the relative capacitance of the top and bottom dielectrics.

*Work supported by DOE Office of Fusion Energy Science and NSF.

†Now with Joint Institute for High Temperatures RAS, Moscow, Russia.

14:30

ET3 4 Charge transfer in surface barrier discharge on μ sec to msec time scales SERGEY LEONOV, IGOR ADAMOVICH, VITALY PETRISHCHEV, *The Ohio State University* OSU TEAM The paper presents experimental results characterizing dynamics of development and kinetics of energy coupling in surface dielectric barrier discharge (SDBD), sustained over dielectric and weakly conducting liquid surfaces, over a wide range of time scales and electrical conductivities. Time-resolved discharge development and mechanisms of coupling with quiescent air are analyzed using nanosecond gate camera imaging, high-sensitivity time-resolved schlieren imaging, surface charge sensor, and Laser Differential Interferometry. It is shown that NS SDBD plasmas generate high-amplitude, broadband, stochastic, point-wise, near-surface perturbations on a long time scale (>100 μs) after the discharge pulse. These perturbations are caused by discharge contraction and originate from the ends of individual streamers where they attach to the surface. It is also demonstrated a significant increase of energy (surface charge) stored on the dielectric surface during the NS discharge pulse, which in this case greatly exceeds energy dissipated as Joule heat (up to a few hundred percent). The present results strongly suggest that surface charge accumulation, along with use of alternating polarity pulse waveform, may significantly improve performance of surface discharge plasma actuators.

SESSION FT1: PLASMA SURFACE INTERACTIONS

Tuesday Afternoon, 4 November 2014; Room: State EF at 15:30; Kenji Ishikawa, Nagoya University, presiding

Invited Papers

15:30

FT1 1 Smart material-based radiation sources*

SCOTT KOVALESKI, *University of Missouri*

From sensors to power harvesters, the unique properties of smart materials have been exploited in numerous ways to enable new applications and reduce the size of many useful devices. Smart materials are defined as materials whose properties can be changed in a controlled and often reversible fashion by use of external stimuli, such as electric and magnetic fields, temperature, or humidity. Smart materials have been used to make acceleration sensors that are ubiquitous in mobile phones, to make highly accurate frequency standards, to make unprecedentedly small actuators and motors, to seal and reduce friction of rotating shafts, and to generate power by conversion of either kinetic or thermal energy to electrical energy. The number of useful devices enabled by smart materials is large and continues to grow. Smart materials can also be used to generate plasmas and accelerate particles at small scales. The materials discussed in this talk are from non-centrosymmetric crystalline classes including piezoelectric, pyroelectric, and ferroelectric materials, which produce large electric fields in response to external stimuli such as applied electric fields or thermal energy. First, the use of ferroelectric, pyroelectric and piezoelectric materials for plasma generation and particle acceleration will be reviewed. The talk will then focus on the use of piezoelectric materials at the University of Missouri to construct plasma sources and electrostatic accelerators for applications including space propulsion, x-ray imaging, and neutron production. The basic concepts of piezoelectric transformers, which are analogous to conventional magnetic transformers, will be discussed, along with results from experiments over the last decade to produce micro-thrusters for space propulsion and particle accelerators for x-ray and neutron production.

*Support from ONR, AFOSR, and LANL.

Contributed Papers

16:00

FT1 2 Simulation of the Vapor Shield Effect on Plasma Facing Materials under Tokomak-Like Disruption Conditions NOUF ALMOUSA, MOHAMED BOURHAM, *North Carolina State University* Hard disruptions are expected in large tokomaks, where plasma-facing components (PFCs) receive radiant high heat fluxes resulting in surface melting and evaporation. The boundary layer at the ablating/melting surfaces absorbs a fraction of the heat flux and a vapor shield effect protects the PFCs from further erosion. The energy transmission factor through the vapor shield f_{vs} is modeled in a 1-D, time dependent code to calculate the erosion under disruption-like conditions of 55 GW/m^2 over 150 μs. The f_{vs} value was found to be strongly dependent on materials properties, plasma pressure, and density, but weakly dependent on the plasma internal and kinetic energies. Calculations of f_{vs} at each time step and mesh point are used to predict the ablated mass. The code predictions are used to estimate the erosion rate and erosion thickness for varies PFMs. It has been found that high-Z PFMs suffer higher ablation rate as compared to low-Z PFMs. However, the erosion in units of material thickness indicates that the erosion thickness of the highest Z PFMs (tungsten) is less than that of the lowest Z PFMs (beryllium). Detailed comparisons of the erosion behavior and properties of PFMs are presented.

16:15

FT1 3 Ion induced electron emission from semiconductors: The effect of conduction band electrons and surface electric fields* DAVID URRABAZO, MATTHEW GOECKNER, LAWRENCE OVERZET, *University of Texas at Dallas* A few recent publications point to the possibility of controlling the ion induced electron emission (IIEE) yield from semiconductor surfaces in real time through controlling the numbers of electrons in the semiconductor's conduction band (ne,CB). Of course, ion bombardment induced electron emission also occurs in the plasma processing of semiconductors, and should cause differences between processing n- and p-type wafers if it truly depends upon ne,CB. Hagstrum's Auger neutralization theory for semiconductors assumes that the IIEE yield should NOT depend upon ne,CB, and as a result most models make the assumption that the IIEE yield is independent of ne,CB (and the position of the Fermi level as well as temperature). To our knowledge, no one has investigated this assumption! Therefore, we have experimentally and theoretically investigated it by using and extending Hagstrum's theory as well as by measuring the IIEE yield from semiconductor samples versus doping density and type. In addition, we have begun both theoretical and experimental investigations into the effects of a surface E-field on IIEE for semiconductors. We will introduce a device we have designed, modeled, and begun fabricating for measuring the IIEE yield while independently controlling the ion flux and E-field.

*This material is based upon work supported by the Department of Energy under Award Number DE-SC-0009308.

16:30

FT1 4 A Comparative Study of Polymer and Biomolecule Surface Modifications by an Atmospheric Pressure Plasma Jet and Surface Microdischarge in Controlled Environments* ELLIOT BARTIS, ANDREW KNOLL, PINGSHAN LUAN, CONNOR HART, JOONIL SEOG, GOTTLIEB OEHRLEIN, *University of Maryland, College Park* DAVID GRAVES, *University of California, Berkeley* WALTER LEMPERT, *The Ohio State University* In this work, polymer- and lipopolysaccharide-coated Si substrates were exposed to a surface microdischarge (SMD) and an atmospheric pressure plasma jet (APPJ) in controlled ambients. We seek to understand how plasma-ambient interactions impact biodeactivation and surface modifications by regulating the ambient gas chemistry and the proximity of the plasma to the ambient. A key difference between the SMD and APPJ is that the APPJ needs an Ar feed gas and the SMD does not. By adding small N_2/O_2 admixtures to Ar, we find that the O_2 admixture in the APPJ is a key factor for both deactivation and surface modification. After plasma treatments, we detected a new chemical species on a variety of surfaces that was identified as NO_3. We find that NO_3 forms even with no N_2 in the feed gas, demonstrating that this species forms due to interactions with ambient N_2. Despite a very different discharge mechanism, the SMD modifies surfaces similarly to the APPJ, including NO_3 formation. The SMD generates large O_3 concentrations, which do not correlate with NO_3, suggesting that O_3 alone is not involved in the NO_3 formation mechanism.

*The authors gratefully acknowledge financial support by the US Department of Energy (DE-SC0005105 and DE-SC0001939) and National Science Foundation (PHY-1004256).

16:45

FT1 5 Non-thermal equilibrium plasma-liquid interactions with femtolitre droplets* PAUL MAGUIRE, CHARLES MAHONY, ANDREW BINGHAM, JENISH PATEL, DAVID RUTHERFORD, DAVID MCDOWELL, DAVIDE MARIOTTI, *University of Ulster* EUAN BENNET, HUGH POTTS, DECLAN DIVER, *University of Glasgow* Plasma-induced non-equilibrium liquid chemistry is little understood. It depends on a complex interplay of interface and near surface processes, many involving energy-dependent electron-induced reactions and the transport of transient species such as hydrated electrons [1]. Femtolitre liquid droplets, with an ultra-high ratio of surface area to volume, were transported through a low-temperature atmospheric pressure RF microplasma with transit times of 1–10 ms. Under a range of plasma operating conditions, we observe a number of non-equilibrium chemical processes that are dominated by energetic electron bombardment. Gas temperature and plasma parameters ($n_e \sim 10^{13}$ cm^{-3}, $T_e < 4$ eV) were determined while size and droplet velocity profiles were obtained using a microscope coupled to a fast ICCD camera under low light conditions. Laminar mixed-phase droplet flow is achieved and the plasma is seen to significantly deplete only the slower, smaller droplet component due possibly to the interplay between evaporation, Rayleigh instabilities and charge emission [2].

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

[1]Mariotti *et al.*, Plasma Process. Polym. **9**, 1074 (2012).
[2]E. Bennet *et al.*, New J. Phys. (submitted).

17:00

FT1 6 Effect of Cryogenic Cooling for Gallium Nitride Film Placed in Argon Plasma DAISUKE OGAWA, YOSHITAKA NAKANO, KEIJI NAKAMURA, *Chubu University* There is no doubt for a gallium nitride (GaN) film to have plasma-induced damage (PID) when exposed in a plasma discharge. Our technique to make in-situ monitoring on a GaN film exposed in argon plasma is valuable toward to reveal the evolution of the damage. We evaluated the PID with photoluminescence (PL) that is excited with a ultra-violet light source. Our preliminary result showed that the PL intensity at the blue luminescence band (BL: 400–480 nm) increased while the intensity at yellow luminescence (YL: 480–700 nm) decreased as the plasma exposure time increased. Chen *et al.* previously found that PL spectrum changes due to both PID and substrate temperature. However, BL intensity is independent from the substrate temperature, while BL intensity is dependent on the degree of PID. In this experiment, we performed the plasma exposure to a GaN film under the situation when the substrate temperature was cooled with liquid nitrogen. The substrate temperature is set at -110 degC and exposed plasma in 15 minutes. In this condition, our BL stayed almost constant. This is an indication that we might be able to avoid the damage in the wavelength shorter than 480 nm. We will show more details from this results and further progresses in this presentation.

17:15

FT1 7 Study of the effect of pressure on thermionic emission current JOHN HAASE, DAVID GO, *University of Notre Dame* Thermionic emission is the process in which heating a cathode allows electrons to gain sufficient energy to overcome the material's work function and be ejected into vacuum. By collecting the emitted electrons at a lower temperature anode and passing them through a load, the thermal energy is directly converted into electrical energy in a process called thermionic energy conversion (TEC). Operating a plasma in the interstitial gap between the cathode and anode produces positive space charge to offset the negative electrons and can improve TEC performance. However, this necessarily requires that the TEC device operates at pressures higher than vacuum. The introduction of a gas between the electrodes of a TEC device can either attenuate, due to elastic collisions, or increase, due to ionization, the current, and this is a strong function of the driving potential from the cathode to anode. In this work, the collected current from thermionic emission in noble gases is examined over a range of pressures and potentials, both experimentally and using kinetic particle-in-cell/Monte Carlo collision (PIC/MCC) simulations. Initial theoretical, simulation, and experimental results show that for electrons with energies below the ionization energy the current i scales with pressure p as $i \propto p^{-n}$, where $\frac{1}{2} \leqslant n \leqslant 1$.

SESSION FT2: CAPACITIVE DISCHARGES - COMPUTATIONAL

Tuesday Afternoon, 4 November 2014
Room: State C at 15:30
Uwe Czarnetzki, Ruhr-Universität Bochum, presiding

Contributed Papers

15:30

FT2 1 Tailoring plasma properties through the non-linear frequency coupling of odd harmonics ANDREW GIBSON, *Centre for Plasma Physics, Queen's University Belfast, Belfast, BT7 1NN* ARTHUR GREB, *York Plasma Institute, Department of Physics, University of York, York, YO10 5DD* WILLIAM GRAHAM, *Centre for Plasma Physics, Queen's University Belfast, Belfast, BT7 1NN* TIMO GANS, *York Plasma Institute, Department of Physics, University of York, York, YO10 5DD* Multiple frequency plasma sources are commonplace in plasma based nano-fabrication. However the control of plasma properties in these discharges is often limited by a poor understanding of the non-linear coupling between the frequencies. Thus investigations of this non-linear coupling are crucial for achieving better control of plasma processes and optimising process outcomes. Presented here is a study of plasma excitation by two coupled odd harmonics (13.56 and 40.68 MHz) using a 1D fluid model of a symmetric capacitively coupled plasma. Non-linear frequency coupling is found to minimise the average plasma potential when both frequencies contribute equally to the voltage waveform. Furthermore, varying the phase between the frequencies can further decrease the average plasma potential, without having a significant effect on the ion density. This effect allows for control of the sheath potential at both electrodes simultaneously, independent of the ion density. As such the use of odd harmonics offers a novel method of plasma control that maintains the symmetry of the discharge. This is in contrast to plasma control techniques utilising the electrical asymmetry effect where the sheath potential is decreased at one electrode by increasing it at the opposing electrode.

15:45

FT2 2 Particle-in-cell Monte Carlo collision simulation of a capacitively coupled discharge in oxygen JON TOMAS GUDMUNDSSON, *University of Iceland* MICHAEL A. LIEBERMAN, *Department of Electrical Engineering and Computer Sciences, University of California at Berkeley* The oopd1 particle-in-cell Monte Carlo collision (PIC-MCC) code is used to simulate a capacitively coupled discharge in oxygen. oopd1 is a one-dimensional object-oriented PIC-MCC code in which the model system has one spatial dimension and three velocity components [1]. The oxygen model includes, in addition to electrons, the oxygen molecule in the ground state, the oxygen atom in the ground state, the negative ion O^-, the positive ions O^+ and O_2^+, and the metastable states $O(^1D)$ and $O_2(a^1\Delta_g)$. We explore the electron energy distribution function (EEDF), the electron temperature profile, the density profiles of charged particles and electron heating rates for a capacitively coupled oxygen discharge. We explore the influence of the metastables on the plasma parameters and in particular the influence of detachment by the metastable $O_2(a^1\Delta_g)$ molecule on the electron heating mechanism in the discharge.

[1] J. T. Gudmundsson, E. Kawamura, and M. A. Lieberman, Plasma Sources Sci. Technol. **22**, 035011 (2013).

16:00

FT2 3 Electron beam formation and resonance phenomena in low pressure capacitive rf plasmas SEBASTIAN WILCZEK, JAN TRIESCHMANN, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Ruhr University Bochum* EDMUND SCHÜNGEL, JULIAN SCHULZE, *West Virginia University, Morgantown* ARANKA DERZSI, IHOR KOROLOV, ZOLTÁN DONKÓ, *Wigner Research Center for Physics, Budapest* In capacitively coupled radio frequency discharges the expansion of the modulated plasma sheaths accelerates a fraction of electrons. This consequently leads to various kinds of electron beam formations; one or likely multiple beams are triggered and start propagating. Especially at low pressures, these electrons traverse through the plasma bulk with high kinetic energy and ionize the neutral background gas to sustain the plasma. Under distinct discharge conditions a violation of the quasi-neutrality of the plasma bulk is indicated by a local accumulation of charge density. Consequently, strong electric fields exist even in the center of the discharge. In this work, the electron beam formations are investigated in conjunction with resonance behavior of the discharge by means of 1d3v Particle-In-Cell simulations. It is shown that the driving frequency or higher harmonics of the driving frequency match the local electron plasma frequency, particularly in the bulk region. This is an indication of local resonance phenomena in conjunction with the establishing of distinct electron beam modes being formed. Moreover, this is connected to a change of the local electric field.

16:15

FT2 4 Efficient Modelling of Pulsing CCP Reactors* SCHABNAM NAGGARY, FRANK ATTELN, RALF PETER BRINKMANN, *Ruhr-University Bochum, Institute for Theoretical Electrical Engineering* MUSTAFA MEGAHED, *ESI Group* Pulsed multi-frequency CCP reactors provide additional means to manipulate the plasma characteristics and in particular the ion energy distribution. The interaction of the plasma with the pulse duty cycle and frequency is not fully understood yet, due to complex excitation and de-excitation of the rf and pulsing signals. Numerical models were demonstrated to accurately capture the transient behavior of the pulsed plasma. The high computational effort, however, makes these models very inaccessible to the community and do not allow for systematic study of the different parameters of interest to system designers. This work presents an efficient model that allows the characterization of the "main" plasma properties including the ion energy distribution functions within seconds. The zero dimensional model allows the analysis of the reactor operation parameter space and it provides the boundary conditions for more detailed, spatially resolved models that are used to fine tune the design including the resolution of wafer edge and wave effects.

*The authors gratefully acknowledge the financial support by the SFB-TR 87 and the ESI Group.

Invited Papers

16:30

FT2 5 Capacitively Coupled Plasma Modeling at Low and Moderately High Pressures
KALLOL BERA, *Applied Materials, Inc.*

Capacitively coupled plasmas have been used in both deposition and etching processes in semiconductor industry. The etching processes are typically performed at low pressure (5–500 mT) as directionality and energy of ions are important. The deposition processes are performed at moderately high pressure (1–10 T) to achieve higher process deposition rates with minimal ion bombardment damage. Our plasma model includes the full set of Maxwell equations in their potential formulation. The equations governing the vector potential are solved in the frequency domain after every cycle for multiple harmonics of the driving frequency. Current sources for the vector potential equations are computed using the plasma characteristics from the previous cycle. The coupled set of equations governing the scalar potential and drift-diffusion equations for all charged species are solved implicitly in time. In the low pressure regime, stochastic heating is important. This effect is considered in the model using modified transport parameters. The model was validating using experimental data. At 13 MHz, secondary electron emission is found to play an important role in enhancing ionization through collisions. At higher frequency, the effect of secondary electron emission is less significant. At very high frequency, the electromagnetic standing wave leads to peak in plasma density at the center of the discharge. In the moderately high pressure regime, secondary electrons are important as they participate in bulk plasma heating. At very high frequency, under moderately high pressure, the electromagnetic effect is also found to be important, with the shape of the plasma profile varying according to aspect ratios of reactor structure. In this paper we will present plasma modeling that adequately represents plasmas at low and moderately high pressures at different frequency.

Contributed Papers

17:00

FT2 6 The effect of ambipolar electric fields on the electron heating in capacitive RF plasmas JULIAN SCHULZE, *West Virginia University* ZOLTAN DONKO, ARANKA DERZSI, IHOR KOROLOV, *Hungarian Academy of Sciences* EDMUND SCHUENGEL, *Department of Physics, West Virginia University* We investigate the electron heating dynamics in argon and helium capacitively coupled RF discharges driven at 13.56 MHz by Particle in Cell simulations and by an analytical model. Electrons are found to be heated by strong ambipolar electric fields outside the sheath during the phase of sheath expansion in addition to classical sheath expansion heating. Moreover, we find that electrons reflected multiple times from the expanding sheath edge within one RF period are the primary sources of ionization. In fact a synergistic combination of different heating events is required to sustain the plasma. The ambipolar electric field outside the sheath is found to be time modulated due to a time modulation of the electron mean energy caused by the presence of sheath expansion heating only during one half of the RF period at a given electrode. This time modulation results in more heating than cooling on time average. If an electric field reversal is present during sheath collapse, this time modulation will be enhanced. This ambipolar electron heating is found to represent an important heating mechanism, which should be included in models of capacitive RF plasmas.

17:15

FT2 7 A Simplified Model of The Electrical Asymmetry Effect DOUGLAS L. KEIL, EDWARD AUGUSTYNIAK, YUKINORI SAKIYAMA, PAVEL NI, *Lam Research Corporation* Dual Frequency Capacitively Coupled Plasmas (DF CCP) have been used extensively in semiconductor processing. One of the most promising methods for extending CCP technology is the application of the Electrical Asymmetry Effect (EAE). Extensive studies of this effect have appeared in the literature and the effect can be claimed to be reasonably well understood [1]. However, the complexity of the available models often makes them unwieldy for resolving engineering issues and for analysis of test data. In this work it is shown that most of the industrially important features of the EAE effect can be captured with a greatly simplified model. Although approximate, this simplified model enables relatively quick design guidance and simplifies analysis of test data. Electrical measurements of the EAE effect from a commercially relevant CCP plasma deposition tool are presented. These results show good agreement with the model and serve to illustrate the basic features of the model.

[1]U. Czarnetzki *et al.*, Plasma Sources Sci. Technol. **20**, 024010 (2011).

SESSION FT3: GRAPHENE SYNTHESIS; PLASMA LIGHT GENERATION
Thursday Afternoon, 6 November 2014
Room: State C at 15:30
David Smith, General Electric Reserach, presiding

Contributed Papers

15:30

FT3 1 Utilization of plasmas for graphene synthesis* MICHAEL KEIDAR, ALEXEY SHASHURIN, *The George Washington University* Graphene is a one-atom-thick planar sheet of carbon atoms that are densely packed in a honeycomb crystal lattice. Graphene has tremendous range of potential applications ranging from high-speed transistors to electrochemical energy storage devices and biochemical sensors. Methods of graphene synthesis include mechanical exfoliation, epitaxial growth on SiC, CVD and colloidal suspensions. In this work the utilization of plasmas in synthesis process is considered. Types of carbonaceous structures produced by the anodic arc and regions of their synthesis were studied. Ultimate role of substrate temperature and transformations occurring with various carbonaceous structures generated in plasma discharge were considered. Synthesis of well-adhered graphene films on the various substrate materials with controllable flake thickness down to about 2 layers was demonstrated. Optimal synthesis conditions were analyzed.

*This work was supported by National Science Foundation (NSF Grant No. CBET-1249213).

15:45

FT3 2 Functionalization of plasma synthesized advanced carbons* EVA KOVACEVIC, *GREMI UMR 7344 CNRS and Universite d'Orleans* THIBAULT LABBAYE, JOHANNES BERNDT, *GREMI UMR 7344 CNRS et Universite d'Orleans* THOMAS STRUNSKUS, *Chair for Multicomponent Materials, Institute for Materials Science, Christian-Albrechts-University at Kiel* ELENA TATAROVA, JULIO HENRIQUES, *Instituto de Plasmas e Fusao Nuclear, Instituto Superior Tecnico, Universidade de Lisboa* CHANTAL BOULMER-LEBORGNE, *GREMI UMR 7344 CNRS et Universite d'Orleans* We report here about experiments concerning the plasma based functionalization of plasma produced carbon nanotubes and free-standing graphenes. The influence of nitrogen and ammonia plasma on the surface properties is investigated, involving the role of the surface temperature on the functionalization procedure. The effect of the plasma treatment on the different carbon materials is analyzed by means of contact angle measurements, near edge x-ray absorption fine spectroscopy (NEXAFS) and XPS. We will discuss the importance of the plasma characteristics for the formation of amino groups and nitrogen incorporation in the material. The important issues concern: the formation of dangling bonds, destructive effects of plasma-surface interactions and recovery of the surfaces.

*The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement No. 312284.

16:00

FT3 3 Controlled synthesis and electrocatalytic characteristics of Pt nanoparticles-supported nanographene synthesized by in-liquid plasma HIROKI KONDO, TOMOKI AMANO, KENJI ISHIKAWA, MAKOTO SEKINE, MASARU HORI, *Nagoya University* MINEO HIRAMATSU, *Meijo University* NAGOYA UNIVERSITY TEAM, MEIJO UNIVERSITY COLLABORATION We investigated a high-speed synthesis of high-crystallinity nanographenes over 1 micro-gram/min using in-liquid plasma. In this study, nanographene materials with different crystallinity were synthesized using ethanol and 1-butanol. Pt nanoparticles were supported on their surfaces reducing 8 wt%-H_2PtCl_6 in H_2O. G-band and D-band peaks in Raman spectra indicated nanographene materials. Nanographene materials synthesized using ethanol have higher crystallinity than those synthesized using 1-butanol. According to X-ray diffraction patterns, sizes of Pt nanoparticles are almost similar regardless of alcohol types. In cyclic voltammetry characteristics, peaks related to adsorption and desorption of hydrogen were clearly found in the both cases. The platinum effective areas were estimated to be 208.5 and 147.63 m^2/g for the cases using ethanol and 1-butanol, respectively. In addition, after potential cycling tests, nanographene materials synthesized using ethanol show almost no degradation, while those using 1-butanol show a drastic degradation. These results indicate that the higher-density Pt nanoparticles can be supported on the higher-crystallinity nanographene material and they show higher durability.

16:15

FT3 4 Growth of graphene-based films using afterglow of inductively coupled plasma MINEO HIRAMATSU, MASAKAZU TOMATSU, *Meijo University* HIROKI KONDO, MASARU HORI, *Nagoya University* Plasma-enhanced CVD (PECVD) employing methane/hydrogen gases has been used to grow diamond and carbon nanostructures. In the case of graphene growth using PECVD, excessive supply of carbon precursors and ion bombardment on the growing surface would cause secondary nuclei, resulting in small size of graphene grain and degradation in crystallinity. To overcome this issue, in this work, afterglow of inductively coupled plasma (ICP) was used for the growth of graphene. The CVD system is simple and consists of a reaction chamber and a remote radical source that uses an ICP in cylindrical geometry. Methane/hydrogen gases were fed through a quartz tube of 26 mm inner diameter and 20 cm in length. A five-turn rf (13.56 MHz) coil was mounted on the quartz tube. Substrates (Ni-coated Si and Cu foil) were located in the afterglow region of ICP. Growth experiments were carried out for 1-10 min at temperature of 700 C, rf power of 400 W, and total pressure of 100 mTorr. We have successfully fabricated graphene-based films, which was confirmed by the Raman spectrum and SEM image of deposit. We will discuss the planar graphene growth mechanism in terms of precursors and their surface reaction, in conjunction with the growth experiments using microwave plasma and ICP in planar geometry.

16:30

FT3 5 Flickering of thoriated and lanthanized tungsten cathodes THOMAS HOEBING, PATRICK HERMANNS, ANDRE BERGNER, CORNELIA RUHRMANN, *Ruhr-University Bochum* HANNES TRAXLER, INGMAR WESEMANN, *Plansee SE* JUERGEN MENTEL, PETER AWAKOWICZ, *Ruhr-University Bochum* Tungsten cathodes in HID-lamps are commonly doped with rare earth oxides to reduce the work function Φ. A popular dopant ThO_2 decreases Φ from 4.55 eV to 3.0 eV and, therewith, reduces the cathode temperature. La_2O_3-cathodes seem to represent an alternative, since the reduction of Φ is comparable to that of thoriated cathodes. But a temporally unstable arc attachment can be observed at cathodes doped with La_2O_3. At thoriated cathodes, this flickering can also be detected, but less pronounced. It is attributed to a temporal increase of Φ, induced by a transient shortage of La at the cathode tip. The arc attachment moves from the tip to colder areas of the cathode, where a high amount of La is present. Reasons for a temporal increase of Φ can be attributed to an insufficient transport of oxides from the interior of the cathode and an insufficient return of vaporized La by an ion current from the arc plasma to the cathode. Enrichments of La/Th compounds are formed on the cathode surface providing emitter material in case of a shortage at the tip. Cathode coverage and diffusion in the interior of the electrode, ThO_2- and La_2O_3-electrodes behave differently. Differences and their influence on the stability of the arc will be presented.

16:45

FT3 6 Performance and aging effects of automotive HID-Lamps when replacing thorium in the electrodes ALEXANDER ALEXEJEV, ANDRE BERGNER, THOMAS HOEBING, CORNELIA RUHRMANN, *Ruhr University Bochum* PETER FLESCH, *OSRAM AG, Berlin* JUERGEN MENTEL, PETER AWAKOWICZ, *Ruhr University Bochum* RUHR UNIVERSITY - OSRAM AG COLLABORATION Tungsten electrodes in automotive HID-Lamps up to now are mostly doped with thoriumdioxide (ThO2). The doping decreases the work function Φ of tungsten from 4.55 eV to 3.0 eV, thus leading to a reduced electrode temperature, resulting in an increased lifetime of the lamp. However, usage of thorium is no longer recommendable, due to complicated trade relationships and transportation issues. An alternative filling or doping is being searched for, which should replace thoriumoxide without affecting the lamp performance. The fillings/dopants are usually rare earth iodides/oxides respectively. Rare earths have similar physical properties as thorium in terms of electronegativity and adsorption energy. Theoretically, several of them can replace thorium. The resulting lamp performance is, however, greatly affected even by minor changes in the filling/doping. The effect of each new component has therefore to be studied by an investigation of the electrode behaviour during lamp operation. The authors present different lamp configurations and their performances, being shown by optical observation and electrode temperature measurements, as well as the aging effects of the investigated lamps.

17:00

FT3 7 Optically Pumped Lasing of Ar(4p→4s) Excited in Linear Microplasma Arrays at Atmospheric Pressure* WILSON RAWLINS, KRISTIN GALBALLY-KINNEY, STEVEN DAVIS, *Physical Sciences Inc., Andover MA* ALAN HOSKINSON, JEFFREY HOPWOOD, *Electrical and Computer Engineering Department, Tufts University, Medford MA* The optically pumped rare-gas metastable laser is a chemically inert analogue to alkali laser systems. These devices require efficient generation of electronically excited metastable atoms in a continuous-wave electric discharge in flowing gas mixtures at elevated pressure. Linear arrays of microstrip resonators are well suited for this task. We have observed CW optical gain and lasing at 912 nm using linear micro-discharge arrays to generate metastable rare-gas atoms at atmospheric pressure. Ar(4s) metastables are generated in flowing Ar/He mixtures by low-power, CW linear array microplasmas operating near 900 MHz and 1 atm. The metastables are optically excited to selected states in the Ar(4p) manifold by a tunable, CW Ti:S laser. Collisional energy transfer within the manifold produces a population inversion. The Ar(4s) concentration and the optical gain are probed by tunable diode laser spectroscopy.

*Supported by the Air Force Research Laboratory and High Energy Laser Joint Technology Office.

17:15

FT3 8 Plasma Formation During Operation of a Diode Pumped Alkali Laser (DPAL) in Cs* NATALIA YU. BABAEVA,† *University of Michigan* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* MARK J. KUSHNER, *University of Michigan* Diode pumped Alkali Lasers (DPALs) produce laser action on the resonant lines of alkali atoms. Diode lasers resonantly pump the $^2P_{3/2}$ state of the alkali atom which is collisionally relaxed to the $^2P_{3/2}$ state which then lases to the ground state $^2S_{1/2}$. The low optical quality of high power semiconductor diode lasers is converted into high optical quality laser radiation from the alkali vapor. The Cs DPAL system using Ar/Cs/C_2H_6 mixtures has shown promising results. (C_2H_6 is the collisional relaxant.) In other studies, resonant excitation of alkali vapor by low power lasers has been used to produce highly ionized channels, initiated through associative ionization and superelastic electron heating. The issue then arises if plasma formation occurs during DPAL by similar mechanisms which would be detrimental to laser performance. In this paper, we report on results from a computational study of a DPAL using Cs vapor. The global model addresses quasi-cw pumping of the Cs($^2P_{3/2}$) state by laser diodes, and includes a full accounting of the resulting electron kinetics. To enable this study, the B-spline R-matrix (BSR) with pseudostates method was employed to calculate electron impact cross sections for Cs. We found that for pump rates of many to 10 kW/cm^2, plasma densities approaching 10^{13} cm^{-3} occur during laser oscillation with higher values in the absence of laser oscillation.

*Supported by DoD High Energy Laser Mult. Res. Initiative and NSF.

†Now with Joint Institute for High Temperatures RAS, Moscow, Russia.

SESSION GT1: POSTER SESSION I (17:30-19:30)
Tuesday Evening, 4 November 2014
Exhibit Exhibit Hall at 17:30

GT1 1 Air mode waveguide cavity with hybrid tunable plasma switching elements for K-band microwaves BENJAMIN WANG, MARK CAPPELLI, *Stanford University* A tapered holey waveguide with an air mode cavity was designed with plasma switching elements. The propagation of microwaves in this device was investigated experimentally and computationally. Finite difference time domain (FDTD) simulations confirm unique resonance modes for plasma on and plasma off states. Integration of low-pressure plasma elements into this hybrid device allowed for controllable propagation of electromagnetic waves, showing tunable band gaps and resonance states.

GT1 2 Difference in Rotational Temperatures between Neutral Molecules and Molecular Ions of Low-Pressure Discharge N2-O2 Plasmas HIROSHI AKATSUKA, HIROKAZU KAWANO, KOICHI NAOI, HAO TAN, ATSUSHI NEZU, HARUAKI MATSUURA, *Tokyo Institute of Technology* For a microwave discharge nitrogen plasma with its discharge pressure about 1 Torr, our OES measurement showed that the rotational temperature of N_2^+ B state by the first negative system (1NS) is about 1.5 times higher than that of N_2 C state by the second positive system (2PS). Meanwhile, it is found that the rotational temperature of O_2^+ b state by 1NS is almost the same as that of O_2 b state by the atmospheric absorption band, which is quite different from N_2 plasma. We consider that the rotational temperature of the ground state O_2^+ X ion should be higher than that of O_2^+ b state due to difference in the internuclear distance, where that of the O_2^+ b state is much larger than that of the ground state O_2^+ X. The angular momentum of both X and b states are almost conserved before and after the electron impact excitation due to small mass of an electron. Therefore, the rotational temperature of the X state of O_2^+ ion should be estimated to be about 1.3 times of that of O_2^+ b state. This value gives a similar result with that of nitrogen plasma, where the internuclear distances of B and X states of N_2^+ are almost the same. It is considered that the ground-state molecular ion has higher rotational temperature than neutral molecule.

GT1 3 Global Model of a Fast Ionization Wave in Helium* BENJAMIN YEE, EDWARD BARNAT, *Sandia National Laboratories* JOHN FOSTER, *University of Michigan* Technical challenges inhibit a complete examination of fast ionization waves via empirical means. The high-voltage pulses used to excite these waves can be on the order of nanoseconds or less. Such short timescales require instruments with exceptional sensitivity and bandwidth, but these may not be available or may not exist. In order to more completely understand the energetics of the fast ionization wave, a global model of a helium discharge was developed. We present the results of the model predictions and a comparison to experimental measurements when possible. The model follows 19 neutral helium states, helium ions, and electrons. Among the reactions included in the model are: electron impact ionization, electron (de)excitation, atomic excitation transfer, radiative decay, and radiation trapping. Comparisons demonstrate that the model can accurately predict 2^3S metastable densities, but discrepancies in the measured and predicted emissions indicate a greater than expected number of higher excited states. This suggests the presence of a persistent source of excitation which is believed to be the result of space charge buildup within the system.

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

GT1 4 Modeling the impact of magnetic field on plasma parameters in an electron beam generated argon plasma* GEORGE PETROV, DAVID BORIS, TZVETELINA PETROVA, SCOTT WALTON, *Naval Research Laboratory* A spatially averaged model of an electron beam generated plasma is developed to model the impact of an externally applied magnetic field on the formation of the electron energy distribution function in an argon background. The model is based on numerical solution of the electron Boltzmann equation that is self-consistently coupled to a set of rate balance equations for electrons and argon ions. The confining effect of the magnetic field is studied theoretically by calculating the electron energy distribution function, electron density and temperature as a function of the magnetic field strength in the range 0–300 Gauss. It was established that a rigorous kinetic treatment, which accounts for the impact of the magnetic field over the whole distribution of electrons, is required for accurate description of the plasma.

*Work supported by the NRL 6.1 Base Program.

GT1 5 Controlling the Electron Energy Distribution Function Using an Anode* SCOTT D. BAALRUD, *University of Iowa* EDWARD V. BARNAT, MATHEW M. HOPKINS, *Sandia National Laboratory* Positively biased electrodes inserted into plasmas influence the electron energy distribution function (EEDF) by providing a sink for low energy electrons that would otherwise be trapped by ion sheaths at the chamber walls. We develop a model for the EEDF in a hot filament generated discharge in the presence of positively biased electrodes of various surface areas, and compare the model results with experimental Langmuir probe measurements and particle-in-cell simulations. In the absence of an anode, the EEDF is characterized by a cool trapped population at energies below the sheath energy, and a comparatively warm tail population associated with the filament primaries. Anodes that are small enough to collect a negligible fraction of the electrons exiting the plasma have little affect on the EEDF, but as the anode area approaches $\sqrt{m_e/m_i}A_w$, where A_w is the chamber wall area, the anode collects most of the electrons leaving the plasma. This drastically reduces the density of the otherwise trapped population, causing an effective heating of the electrons and a corresponding density decrease. A global model is developed based on the EEDF model and current balance, which shows the interconnected nature of the electron temperature, density and the plasma potential.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contract DE-AC04-94SL85000, and by the University of Iowa Old Gold Program.

GT1 6 Effect of mass and charge of ionic species on spatio-temporal evolution of transient electric field in CCP discharges SARVESHWAR SHARMA, SANJAY KUMAR MISHRA, PREDHIMAN KAW, *Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India* MILES TURNER, *Dublin City University, Glasnevin, Dublin 9, Ireland* SHANTANU KUMAR KARKARI, *Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India* The formation of capacitive sheath and existence of the transition electric field between sheath edge and bulk plasma in RF-CCP discharge is predicted by Kaganovich (PRL **89**, 265006 2002); such structures are sensitive to the plasma composition. On the basis of semi-infinite particle-in-cell (PIC) simulation the effect of charge and mass of ionic species on the spatio-temporal evolution of the transient electric field and phase mixing phenomena in linear and weakly nonlinear regime has been explored. As an important feature, the simulation results predict that the maximum amplitude of the transient electric field decreases while the potential structure approaching to the electrode with increasing ionic mass and charge. The excitation of wave like structures in the transition region and efficient energy transport to the bulk region of CCP discharges in a nonlinear regime has also been predicted.

[1] I. D. Kaganovich, Phys. Rev. Lett. **89**, 265006 (2002).
[2] I. D. Kaganovich, O. V. Polomarov, and C. E. Theodosiou, IEEE Trans. Plasma Sci. **34**, 696 (2006).

GT1 7 Tuning of Electron Energy and Density in a Double-Pulsed Argon Plasma* RICKY TANG, EDWARD BARNAT, PAUL MILLER, *Sandia National Laboratories* The ability to tune the properties of a plasma was demonstrated with a double-pulsed positive column discharge. The plasma is generated by the first voltage pulse, which sets the peak electron density. A subsequent voltage pulse is applied during the afterglow to achieve independent tuning of the electron energy. Experiments were conducted over a range of voltage pulse amplitudes. Microwave resonant cavity (MRC) measurements of electron density and temperature demonstrated operating conditions, such as relative pulse amplitude and pulse width, where the electron temperature can be independently adjusted without affecting the density. Laser absorption measurements of the concentration of the 1S4 and 1S5 metastable states of argon corroborate the MRC measurements, demonstrating an increase in metastable density while the electron density continues its decay after the initial pulse. Electron drift velocity calculation also shows the dependence of the electron energy on the second voltage pulse. Results from the two diagnostics demonstrate the ability to tune the E/N ratio of the plasma, and hence the mean electron energy, independently of the density.

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

GT1 8 Controlling plasma properties in a dc discharge with two anodes and a cold cathode* VLADIMIR DEMIDOV, *WVU and SPbGU* EVGENY BOGDANOV, *SPbGU* MARK KOEPKE, *WVU* ANATOLY KUDRYAVTSEV, *SPbGU* IYA KURLYANDSKAYA, *SPbU SES* OLGA STEPANOVA, *SPbGU* Understanding the interaction between sheath and contacting electrodes is important for predicting plasma kinetics and controlling plasma properties for various applications where the plasma is volumetrically confined. To demonstrate controlling electron temperature in nonlocal plasma, modeling a dc discharge with cold cathode and application of different voltages to the discharge anodes has been performed. The modeling has been conducted in low-pressure argon gas discharge. It has been demonstrated that applied voltage can modify trapping within the device volume the energetic electrons arising from atomic and molecular processes in the plasma and emitted from the cathode due to ion bombarding. This leads to transformation of heating slow electrons by energetic electrons and as a result modifies the electron temperature. This also leads to modification of spatial distribution of densities of charged and excited metastable atom particles and plasma potentials. The above effects have also been experimentally demonstrated in short (without positive column) dc discharges of various constructions.

*This work has been supported by DoE and SPbGU.

GT1 9 Experimental study of low-temperature plasma transport across a magnetic filter* ROMAIN BAUDE, FREDDY GABORIAU, GERJAN HAGELAAR, *LAPLACE, CNRS and University of Toulouse* Magnetized low-temperature plasmas are widely used in fields like space propulsion, materials processing or neutral beam injection. Charged particle transport in these plasmas is complex and still not fully understood. This paper presents an experimental study of plasma transport across a magnetic barrier as used in various (negative) ion sources. The aim is to obtain experimental data that are sufficiently detailed to provide direct insight into the physical principles of the cross-field transport and to validate numerical simulations. For this purpose we developed a dedicated laboratory set-up featuring an inductive argon discharge connected with a magnetic filter region. A segmented wall probe was used to measure the spatial profiles of the electron and ion current densities across the filter, while the plasma parameters were measured at different positions with a Langmuir probe. Measurements were performed for different gas pressures, magnetic field strengths, and bias voltages. The results clearly demonstrate the transition between a collisional regime where the electron current varies as 1/B2 and a bounded-drift regime with asymmetric electron temperature and 1/B current.

*This work is supported by French National Research Agency (Project METRIS ANR-11-JS09-008).

GT1 10 Breakdown in vapors of alcohols: methanol and ethanol* ZORAN LJ. PETROVIC, JELENA SIVOS, NIKOLA SKORO, DRAGANA MARIC, GORDANA MALOVIC, *Institute of Physics, University of Belgrade* Breakdown data for vapors of the two simplest alcohols – methanol and ethanol – are presented. The breakdown is achieved between plan-parallel electrodes, where cathode is made of copper and anode is a thin film of platinum deposited on quartz window. Diameter of electrodes is 5.4 cm and electrode gap 1.1 cm. We compare breakdown voltages (Paschen curves) for methyl and ethyl alcohol in the pressure range 0.1–2 Torr. In both vapors, the pressure is kept well below the vapor pressure, to prevent formation of liquid droplets. For each point of Paschen curves corresponding axial profiles of emission are recorded by ICCD camera in visual part of the spectra. Axial intensity distributions reveal important processes of excitation. Both vapors show strong emission peak near the cathode at all pd values covered by measurements, which indicates that excitation by ions and fast neutrals play important role in the discharge. Preliminary spectrally resolved measurements of the discharge structure with optical filters show that dominantly emission comes from CH band at 431 nm. There is a very low intensity of Hα emission detected in ethanol vapor at high E/N, while it is much stronger in methanol even at lower E/N. It is interesting to note that Hα emission in methanol exhibits exponential increase of intensity from the cathode to the anode, so it comes mainly from excitation by electrons, not heavy particles.

*Supported by MESTD Projects ON171037 and III41011.

GT1 11 Electron heating due to coulomb collisions between slow and intermediate electrons in DC glow discharges STEPAN ELISEEV, ANATOLIY KUDRYAVTSEV, *Saint Petersburg State University* As is known, the electrons in the cathode glow discharge plasma (negative glow and Faraday dark space) can be divided into three groups - slow, intermediate and fast electrons. Slow electrons, having maximum density, provide quasi-neutrality. They're locked in a potential well and have Maxwellian energy distribution. Fast electrons gain their energy in the cathode fall and maintain sufficient ionization in discharge. Intermediate electrons originate during ionization by fast electrons and carry current in the discharge. They have energies up to the threshold of inelastic collisions in the gas. At the same time they carry out their energy to the walls of the discharge and spend it on elastic collisions with gas atoms and Coulomb collisions with slow electrons and heat them. The amount of heating depends on the degree of ionization of gas, pressure, discharge tube size etc. The paper presents the results of a study on the impact of the heating on temperature and concentration of slow electrons in glow discharge.

GT1 12 Investigation of power dependence of electron density for various pressures JUNE YOUNG KIM, DONG-HWAN KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University, Seoul 133-791, South Korea* JU HO KIM, SANG-BUM JEON, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, Seoul 133-791, South Korea* Experimental observation of the electron density variation in inductively coupled plasmas with the electron energy probability function was performed at various gas pressures at two RF input powers (25 W, 200 W). The measured electron energy probability functions (EEPFs) at high power discharges (200 W) showed a Maxwellian distribution, while evolution of the EEPFs from a bi-Maxwellian distribution to a Druyvesteyn-like distribution was observed at low RF powers (25 W) with increasing pressure. A discrepancy of the electron density variation between the two RF input powers was observed, and it was explained by the modified collisional loss and the Bohm velocity from the electron energy probability functions of the bi-Maxwellian distribution and the Druyvesteyn -like distribution.

GT1 13 DBCC Software as Database for Collisional Cross-Sections DANIEL MOROZ, *University of Pennsylvania* PAUL MOROZ, *Tokyo Electron U.S. Holdings, Inc.* Interactions of species, such as atoms, radicals, molecules, electrons, and photons, in plasmas used for materials processing could be very complex, and many of them could be described in terms of collisional cross-sections. Researchers involved in plasma simulations must select reasonable cross-sections for collisional processes for implementing them into their simulation codes to be able to correctly simulate plasmas. However, collisional cross-section data are difficult to obtain, and, for some collisional processes, the cross-sections are still not known. Data on collisional cross-sections can be obtained from numerous sources including numerical calculations, experiments, journal articles, conference proceedings, scientific reports, various universities' websites, national labs and centers specifically devoted to collecting data on cross-sections. The cross-sections data received from different sources could be partial, corresponding to limited energy ranges, or could even not be in agreement. The DBCC software package was designed to help researchers in collecting, comparing, and selecting cross-sections, some of which could be constructed from others or chosen as defaults. This is important as different researchers may place trust in different cross-sections or in different sources. We will discuss the details of DBCC and demonstrate how it works and why it is beneficial to researchers working on plasma simulations.

GT1 14 Anode Sheath and Double Layer Solutions with Ionization* BRETT S. SCHEINER, SCOTT D. BAALRUD, *Department of Physics and Astronomy, University of Iowa* When an electrode in a plasma is biased more positive than the plasma potential it attracts electrons and repels ions forming a region of negative space charge (electron sheath). Ballistic electrons moving towards this anode gain energy equal to the difference in electrostatic potential energy, $\Delta\phi = \phi(x) - \phi_{\text{plasma}}$, with a maximum of $\phi_{\text{anode}} - \phi_{\text{plasma}}$. When ϕ_{anode} is large enough, electrons can gain enough energy to ionize neutral atoms through electron impact ionization. This leads to a layer of increased ion density near the anode, which can exceed the local electron density at large enough anode biases forming a double layer. We model the sheath potential profile using Poisson's equation with a fluid model for the electron density in the case without ionization and formulate an integral equation for the case with ionization where the ion density depends on an integral from $\phi(x)$ to ϕ_{anode}. An analytic form of the sheath electric field is obtained for the case without ionization and we demonstrate that it asymptotically agrees with the Child-Langmuir solution. We numerically obtain double layer solutions when including ionization and show that the potential profile expands beyond that of the Child-Langmuir solution.

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

GT1 15 Does the Bohm Criterion have meaning for collisional plasmas?* GREG SEVERN, *University of San Diego, Department of Physics* CHI-SHUNG YIP, SIROUS NOURGOSTAR, NOAH HERSHKOWITZ, *University of Wisconsin-Madison, Department of Engineering Physics* Theorists view the Bohm criterion as approximately true, holding only for collisionless plasmas. The question of whether there exists a collisionally modified Bohm Criterion (CMBC) is often answered in the negative, and it is only a question of how the Bohm Criterion fails for the case of finite collisionality. The question is of importance considering that nearly all practical plasma processing applications involve plasmas of finite collisionality. There is, however, very little experimental work to help choose between competing models of how Bohm's Criterion fails. The question of critical importance is this: in plasmas of finite collisionality, do ions reach the Bohm speed at the location where the quasineutral plasma ends and where space charge appears? We have begun to examine the question experimentally in single ion species plasmas, and our goal is to vary the ion-neutral mean free path λ within the interval $1 < \lambda/\lambda_D < 10^3$, where λ_D is the Debye length, and to present both plasma potential data and ion velocity distribution function profiles, measured by emissive probes and by LIF, respectively, to help us understand and assess the validity of theoretical claims.

*Work supported by NSF Grant No. PHY-1206421, CBET-0903783, and CBET-0903832, and U.S. Department of Energy (DOE) Grant Nos. DE-FG02- 97ER54437 and DE FG02-03ER54728.

GT1 16 First steps towards the reaction kinetics of HMDSO in an atmospheric pressure plasma jet in argon* DETLEF LOFFHAGEN, MARKUS M. BECKER, RÜDIGER FOEST, JAN SCHÄFER, FLORIAN SIGENEGER, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* Hexamethyldisiloxane (HMDSO) is a silicon-organic compound which is often used as precursor for thin-film deposition by means of plasma polymerization because of its high deposition rate and low toxicity. To improve the physical understanding of the deposition processes, fundamental investigations have been performed to clarify the plasma-chemical reaction pathways of HMDSO and their effect on the composition and structure of the deposited film. The current contribution represents the main primary and secondary plasma-chemical processes and their reaction products in the effluent region of an argon plasma jet at atmospheric pressure. The importance of the different collision processes of electrons and heavy particles are discussed. Results of numerical modelling of the plasma jet and the Ar-HMDSO reaction kinetics indicate that the fragmentation of HMDSO is mainly initiated by collisions with molecular argon ions, while Penning ionization processes play a minor role for the reaction kinetics in the effluent region of the jet.

*The work has been supported by the German Research Foundation (DFG) under Grant LO 623/3-1.

GT1 17 Optical emission study of ion composition in an inductively coupled oxygen plasma* NATHANIEL LY, JOHN B. BOFFARD, CHUN C. LIN, AMY WENDT, *University of Wisconsin-Madison* SVETLANA RADOVANOV, HAROLD PERSING, ALEXANDRE LIKHANSKII, *Applied Materials, Silicon Systems Group, Varian Semiconductor Equipment* The success of ion implantation to precisely modify substrate properties requires control of the incident ion energies to achieve the desired depth of the implanted ions. Oxygen plasmas generally contain both O^+ and O_2^+ ions, and in plasma immersion ion implantation (PIII) of oxygen, the two will produce different concentration depth profiles due to their different energy/mass ratios. Predicting the overall profile thus requires knowledge of the relative fluxes of the two ion species. Here we combine experiment and modeling to investigate the feasibility of using non-invasive optical emission spectroscopy (OES) to monitor O^+ and O_2^+ abundances in an oxygen inductively-coupled plasma. Measurements of multiple O, O_2, O^+, and O_2^+ emission line intensities were made as a function of pressure (1-30 mTorr) and power (500–2000 W). While the O_2^+ emissions were relatively intense, the O^+ emissions were very weak for all conditions examined. Emissions from both ion species were highest at low pressures and at the highest power levels, but the O^+/O_2^+ emission ratio varied little with plasma conditions.

*This work was supported in part by NSF Grant PHY-1068670.

GT1 18 Kinetic study of the NO formation in pulsed air-like low-pressure dc plasmas: measurement and numerical modelling MARKO HUEBNER, SERGEJ GORCHAKOV, DETLEF LOFFHAGEN, *INP Greifswald, Germany* OLIVIER GUAITELLA, *LPP, Ecole Polytechnique, France* DANIIL MARINOV, *Open University, UK* ANTOINE ROUSSEAU, *LPP, Ecole Polytechnique, France* JUERGEN ROEPCKE, *INP Greifswald, Germany* INP GREIFSWALD, GERMANY TEAM, LPP, ECOLE POLYTECHNIQUE, FRANCE COLLABORATION The formation of NO has been studied measuring the temporal evolution of the density of NO, NO_2 and N_2O by high time-resolved quantum cascade laser absorption spectroscopy. The densities of these nitrous oxides have been measured in synthetic air as well as in air with an admixture of 1% of NO_2 and N_2O, respectively, at a pressure of 1.33 mbar and mean currents between 50 and 150 mA. The measured time-dependent densities of NO, NO_2 and N_2O have been compared with those calculated by means of a self-consistent numerical model. The modelling approach includes the coupled solution of the time-dependent electron Boltzmann equation and a system of rate equations for various heavy particles. In general, measured and calculated results show good qualitatively agreement. In total four distinct phases of the NO density evolution during the plasma pulse and the early afterglow are found. The densities of NO_2 and N_2O decrease exponentially during the plasma pulse and remain almost constant in the afterglow. The admixture of NO_2 has a remarkable impact on the NO production during the ignition of the plasma. The dominating processes are presented and discussed.

GT1 19 Surface mechanisms during cryogenic etching of silicon with SF_6/O_2 inductively coupled plasmas STEFAN TINCK, *University of Antwerp* THOMAS TILLOCHER, *Université d'Orleans* ANNEMIE BOGAERTS, *University of Antwerp* PLASMANT - GREMI COLLABORATION A computational and experimental study is performed to obtain better insight in the surface reactions occurring during the etching of silicon with SF_6/O_2 inductively coupled plasmas at cryogenic conditions. Cryogenic etching is a promising technique to etch ultra-high aspect ratio nanoscale trenches for fabricating microchips. During cryoetching, the substrate (i.e., a silicon wafer) is cooled down to about −100 °C. Cryoetching has some advantages compared to the well-known Bosch process, like no scalloping of sidewalls and no material residues on the reactor walls. A disadvantage of cryoetching is its sensitivity to operating conditions such as substrate temperature and fraction of oxygen in the SF_6/O_2 mixture. During etching, the sidewalls of the trenches are passivated with a SiF_xO_y layer which prevents lateral etching. When heating the wafer to room temperature, the passivation layer desorbs automatically, leaving a smooth and clean trench. The mechanism of the formation and desorption of this passivation layer at cryogenic temperatures is not well understood and is investigated here. A 2-dimensional hybrid Monte Carlo Fluid plasma model linked with Molecular Dynamics simulations is used for a computational investigation while results are validated by experimentally measured etch rates. The focus is on the reaction mechanisms during cryoetching in comparison with conventional room temperature etching.

GT1 20 Sum frequency generation spectroscopy of interfacial water molecules influenced by plasma-generated radicals TAKAHIRO KONDO, TSUYOHITO ITO, *Osaka Univ.* We report the effects of radicals generated by plasma on the structure of water molecules in the air/water interfacial region by sum frequency generation (SFG) spectroscopy. SFG spectroscopy gives molecular level information for the interfacial region. We used a visible pulse laser (wavelength: 532 nm) and a tunable IR pulse laser (wavenumber: 2850–4000 cm^{-1}) for SFG spectroscopy. Radicals are generated by a dielectric barrier discharge (DBD) in the air, and supplied to the water surface. We found that the peak at about 3700 cm^{-1} in the SFG spectrum tends to decrease when the DBD is generated and the radicals are supplied. When the DBD is turned off, the SFG signal recovers. According to previous studies, the SFG peak at about 3700 cm^{-1} is assigned to the stretch mode of free OH in interfacial water molecules. We believe that the radicals interact with the free OH and disturb the vibration, leading to a decrease of the SFG signal when the DBD is generated. When the DBD is turned off, the SFG signal recovers because there are much less radicals in the air. Details on the experimental results and discussions will be presented at the conference.

GT1 21 Effects of the Fabrication and Preparation Processes on the SEY of Niobium SRF Cavities MILOS BASOVIC, *Old Dominion University, CAS* ANA SAMOLOV, *University of Massachusetts Boston* SVETOZAR POPOVIC, LEPSHA VUSKOVIC, *Old Dominion University, CAS* We are reporting progress on effects of the plasma treated surface on the Secondary Electron Yield (SEY) of Niobium (Nb) samples. Fabrication and preparation processes affect intrinsic quality factor (Q factor) to a great extent contributing to multipacting. Multipacting is a resonant phenomenon occurring as an electron buildup and degrading the maximum Q factor achievable by cavity. Apart from the initial impurities of the Nb sheet metal used for cavity fabrication, additional inclusions on the surface of the cavity are added by forming and welding of the components. Operation of the cavities is affected by these inclusions in such a way that it decreases the overall performance of the accelerators. Performance of the cavities can be improved by manipulating the parameters or by mitigating the consequences of the fabrication and preparation processes. We are testing the influence of the electron beam welding and various surface treatments on Nb samples by measuring the SEY of coin-like samples with the surface treated in several different methods. The system is designed to measure energy distribution of SEY of the samples under several incident angles. Comparison is being made between non-treated and treated surface, as well as effects of each treatment on SEY of the surface. Our aim is to show which of the surface treatments or combination of them are beneficial to reducing SEY of the cavity surface.

GT1 22 Laser-induced Fluorescence and Optical Emission Spectroscopy for the Determination of Reactive Species in the Effluent of Atmospheric Pressure Low Temperature Plasma Jets XUEKAI PEI, *HuaZhong University* HAMID RAZAVI, *Old Dominion University* XINPEI LU, *HuaZhong University* MOUNIR LAROUSSI, *Old Dominion University* OH radicals and O atoms are important active species in various applications of room temperature atmospheric pressure plasma jet (RT-APPJ). So the determination of absolute density of OH radicals and O atoms in RT-APPJs is necessary. In this work, the time and spatially resolved OH radicals density of a RT-APPJ are measured using the laser-induced fluorescence (LIF) technology [1]. In addition, the spatial distribution of the emitting species along the axial direction of the jet is of interest and is measured using optical emission spectroscopy. The absolute OH density of the RT-APPJ is about 2.0×10^{13} cm^{-3} at 5 mm away from the plasma jet nozzle and 1 μs after the discharge. The OH density reaches a maximum when H_2O concentration in helium gas flow is about 130ppm. In order to control the OH density, the effect of voltage polarity, applied voltage magnitude, pulse frequency, pulse width on the OH density are also investigated and discussed. O atoms are investigated by TA-LIF. It is demonstrated that the O atoms density reaches a maximum when O_2 percent is about 0.3% in pure He and the lifetime of O atoms in RT-APPJ is much longer (up to dozens of ms) than OH radicals.

[1]X. Pei, Y. Lu, S. Wu, Q. Xiong, and X. Lu, Plasma Sources Sci. Technol. 22, 0250232 (2013).

GT1 23 Measurement of Gas Temperature in Negative Hydrogen Ion Source by Wavelength-Modulated Laser Absorption Spectroscopy* S. NISHIYAMA, K. SASAKI, *Hokkaido University* H. NAKANO, M. GOTO, M. KISAKI, K. TSUMORI, *National Institute for Fusion Science* NIFS-NBI TEAM Measurement of the energy distribution of hydrogen atom is important and essential to understand the production mechanism of its negative ion (H^-) in cesium-seeded negative ion sources. In this work, we evaluated the temperature of atomic hydrogen in the large-scale arc-discharge negative hydrogen ion source in NIFS by wavelength-modulated laser absorption spectroscopy. The laser beam was passed through the adjacent region to the grid electrode for extracting negative ions. The frequency of the laser was scanned slowly over the whole range of the Doppler width (100 GHz in 1s). A sinusoidal frequency modulation at 600 Hz with a width of 30 GHz was superposed onto the slow modulation. The transmitted laser was detected using a photodiode, and its second harmonic component of the sinusoidal modulation was amplified using a lock-in amplifier. The obtained spectrum was in good agreement with an expected spectrum of the Doppler-broadened Balmer-α line. The estimated temperature of atomic hydrogen was approximately 3000 K. The absorption increased with the arc-discharge power, while the temperature was roughly independent of the power.

*This work is supported by the NIFS Collaboration Research Program NIFS13KLER021.

GT1 24 Correlating Metastable-Atom Density, Reduced Electric Field, and Electron Energy Distribution in the Early Stages of a 1-Torr Argon Discharge* J.B. FRANEK, S.H. NOGAMI, M.E. KOEPKE, V.I. DEMIDOV, *W Virginia Univ* E.V. BARNAT, *Sandia Nat'l Labs* Temporal measurement of electron density, metastable-atom density, and reduced electric field are used to approximate certain reaction rate constants [1] for electron-atom collision excitation in a 1-Torr positive column of argon plasma. This allows us to relate the observed 420.1 nm to 419.8 nm line-intensity ratio to plasma parameters by invoking a plausible assumption regarding the shape of the electron energy distribution function (EEDF) throughout the discharge [1]. We show that these reaction rate constants agree well with experimental observations in the late stages of the pulse, but we do not emphasize the late-stage behavior here. Instead, we address discrepancies in the initiation and transient phases of the discharge. We examine three assumptions made in the model to see if the assumptions are violated in these two stages of the discharge: (1) The stepwise excitation from the 1s4 and 1s2 resonant states is negligible; (2) The numerical model designed for a 5-millitorr plasma is applicable to our 1000-millitorr plasma; and (3) The EEDF is bi-Maxwellian and is modified only slightly due to the presence of electrons or metastable-atoms in the discharge. We conclude that diagnostic signatures for electron density, metastable density, and reduced electric field can be quantitatively interpreted by this correlation at all stages of the discharge [1].

*also St. Petersburgh Univ. Work supported by DOE Grant DE-SC0001939.

[1] Adams *et al.*, Phys. Plasmas **19**, 023510 (2012).

GT1 25 Optical emission diagnostics for plasma parameters in pulse-modulated argon capacitively-coupled discharges* SHICONG WANG, JOHN B. BOFFARD, CHUN C. LIN, AMY E. WENDT, *University of Wisconsin-Madison* Pulsing of discharge power in low pressure rf plasmas is a means to improve materials processing outcomes. Plasma-surface interactions depend on the relative fluxes of ions, reactive neutrals and photons, which can be controlled by adjusting pulse frequency and duty cycle, due their effect on plasma properties, particularly the electron energy distribution. We report on an optical emission spectroscopy (OES) based plasma diagnostic to characterize the time evolution of plasma properties within the pulse cycle for two systems: a pulsed capacitively-coupled plasma (CCP), and a pulsed CCP in combination with a continuous-wave (cw) inductively coupled plasma (ICP); Typical conditions: 30 mTorr Ar, 13.56 MHz rf power (400 W peak CCP and 500 W ICP) and 1 kHz pulse frequency. We quantify the trade off between time resolution versus uncertainty in measured OES intensities. Because only a small fraction of CCP rf power contributes to electron heating, the method is limited by relatively low *absolute* OES intensities for the CCP-only case, and small incremental changes in intensity when the pulsed CCP is combined with the cw ICP. Nevertheless, with sufficient signal averaging, even subtle changes in parameters induced by the CCP in the latter case can be quantified.

*This work was supported in part by NSF Grant PHY-1068670.

GT1 26 Diagnostics of nonlocal plasmas: advanced techniques ALEXANDER MUSTAFAEV, ARTIOM GRABOVSKIY, ANASTASIYA STRAKHOVA, *National University of Mineral Resources "Mining," Department of General and Technical Physics* VLADIMIR SOUKHOMLINOV, *Saint-Petersburg State University, Department of Physics* This talk generalizes our recent results, obtained in different directions of plasma diagnostics. First-method of flat single-sided probe, based on expansion of the electron velocity distribution function (EVDF) in series of Legendre polynomials. It will be demonstrated, that flat probe, oriented under different angles with respect to the discharge axis, allow to determine full EVDF in nonlocal plasmas. It is also shown, that cylindrical probe is unable to determine full EVDF. We propose the solution of this problem by combined using the kinetic Boltzmann equation and experimental probe data. Second-magnetic diagnostics. This method is implemented in knudsen diode with surface ionization of atoms (KDSI) and based on measurements of the magnetic characteristics of the KDSI in presence of transverse magnetic field. Using magnetic diagnostics we can investigate the wide range of plasma processes: from scattering cross-sections of electrons to plasma-surface interactions. Third-noncontact diagnostics method for direct measurements of EVDF in remote plasma objects by combination of the flat single-sided probe technique and magnetic polarization Hanley method.

GT1 27 Radially resolved spectroscopic analysis of positive streamers under transient luminous events conditions* VACLAV PRUKNER, *Institute of Plasma Physics AS CR, v.v.i., Department of Pulse Plasma Systems, Za Slovankou 3, 18200 Prague, Czech Republic* TOMAS HODER, *Leibniz Institute for Plasma Science and Technology - INP Greifswald, Felix- Hausdorff-Str. 2, 17489 Greifswald, Germany* MILAN SIMEK, *Institute of Plasma Physics AS CR, v.v.i., Department of Pulse Plasma Systems, Za Slovankou 3, 18200 Prague, Czech Republic* The Transient Luminous Events (TLE) are huge electrical discharges appearing at the upper atmosphere. Sufficiently spatially and temporally resolved spectroscopy is currently one of the very few methods how to get closer to the basic TLEs parameters. In this study, triggered positive streamers were operated in volume barrier discharge with 4 cm gap fed with synthetic air at pressures between 8.98 and 0.16 torr corresponding to equivalent TLE altitudes ranging from 30 to 60 km, respectively. Time resolved axial and radial emission profiles of streamer channel were collected by scanning the discharge via fast photo-multiplier and spectral band-pass filters. Depending on different streamer velocities, different widths of the streamers were measured. Obtained data were analyzed in order to estimate values of the streamer head electric field with radial resolution.

*Work supported by the AV CR (Project M100431201). Stay of T. Hoder at IPP financed through the ESF TEA-IS (exchange Grant No. 4219).

GT1 28 Measuring of the nonlocal EDF of penning electrons by the wall electrode in the plasma afterglow ANATOLY KUDRYAVTSEV, KIRILL KAPUSTIN, ALMAZ SAYFUTDINOV, *St. Petersburg State University* In [1] was patented ionization detector for gas analysis, based on the method of collisional electron spectroscopy (CES), which allows working at a high gas pressure. The CES method provides an opportunity to analyze energy of nonlocal electrons released during Penning ionization of atomic or molecular impurities by metastable helium atoms. In this case, the EDF of fast electrons will be narrow peaks that correspond to the energies of their appearance in Penning ionization. To realize the CES method at high (atmospheric) pressure the plasma gap must be small $L < 0.1$ mm. In this condition the traditional Langmuir probe is impossible to use for measuring the EDF. To overcome this difficulty in [1] was proposed to use afterglow plasma and one of the electrodes as a measuring probe for the registration of EDF of fast penning electrons. In this paper we simulate the afterglow of argon discharge between parallel electrodes and show that EDF and electron sources of Penning ionization are determined by the first derivative of the current to the wall electrode with respect to potential. This work was supported by RSCF and SPbSU.

[1]A. A. Kudryavtsev and A. B. Tsyganov, US Patent 7,309,992, issued December 18 (2007).

GT1 29 Time-resolved measurements of energy distributions for mass-identified ions in low pressure plasmas DAVE SEYMOUR, ALAN REES, TOM RUSSELL, CLAIRE GREENWOOD, *Hiden Analytical* HIDEN TEAM The direct measurement of energy distributions for mass-identified positive and negative ions arriving at target surfaces in plasma reactors has produced much useful information. The measurements have been, in the great majority of cases, of the time-averaged distributions even when the applied power to the plasma has been pulsed. Time-resolved data particularly during initiation and decay of pulsed plasmas would be advantageous. To facilitate such studies we have incorporated a Multi-Channel Scaler device into the ion detector system of a Hiden EQP instrument. Preliminary data which illustrate the capabilities of the new equipment will be presented. The data were obtained for a number of typical reactor systems. For the first of these the plasma was RF powered, typically at 20 Watts, in nitrous oxide at a pressure of 20 mTorr. The energy distributions for N_2O+, $NO+$ and $O+$ and O-ions were measured throughout the duration of a pulsing cycle with particular emphasis on the ignition and decay of the plasma. The distributions show considerable detail and clear differences between the behaviour of the different ions which reflect differences in their production and decay mechanisms.

GT1 30 Analysis of the harmonic currents in floating probes with dielectric films KYUNG-HYUN KIM, *Department of Electrical Engineering, Hanyang University* DONG-HWAN KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University* JIN-YONG KIM, YU-SIN KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Plasma diagnostics using harmonic currents was firstly used to obtain the electron temperatures and ion densities. In this method, the electron temperature is proportional to the ratio of the harmonic currents due to the sheath non-linearity. Harmonic currents are affected by input voltage, thus calculation of exact voltage across the sheath is important; the voltage is calculated using phase analysis of the probe current. However, in the case of the dielectric deposited probe, rapid decrease of the second harmonic current than expected is observed. To explain this effect, circuit analysis including non-linear elements is adopted, and the calculations using this analysis are compared with experimental results.

GT1 31 On harmonic diagnostic method using two frequencies in a floating Langmuir probe DONG-HWAN KIM, YOUNG-DO KIM, SUNG-WON CHO, YU-SIN KIM, CHIN-WOOK CHUNG, *Hanyang University* Plasma diagnostic methods using harmonic currents analysis of floating probes were experimentally investigated. When dual-frequency voltage (ω_1, ω_2) was applied to a probe, various harmonic currents $(\omega_1, 2\omega_1, \omega_2, 2\omega_2, \omega_2 \pm \omega_1, \omega_2 \pm 2\omega_1)$ were generated due to the nonlinearity of the probe sheath. The electron temperature can be obtained from the ratio of the two harmonics of the probe currents. According to the combinations of the two harmonics, the sensitivities in measurement of the electron temperature differs and this results in the difference in the electron temperature. From experiments and simulation, it is shown that the difference is caused by the random and systematic noise.

GT1 32 Tunable external RF choke filter design for single Langmuir probe in RF discharges SANGBUM JEON, YU-SIN KIM, DONG-HWAN KIM, CHIN-WOOK CHUNG, *Hanyang University* The tunable external RF choke circuit was developed to compensate radio frequency (RF) fluctuation in single Langmuir probe measurement. This method consists of series circuit of each harmonic component of the driving frequency, and has high impedance at the resonance frequencies. The measured electron energy probability functions (EEPFs) from the single Langmuir probe with the external RF compensation circuit were obtained at various discharge conditions, such as gas pressures and RF powers. The EEPFs have highly populated low energy electrons with bi-Maxwellian EEPFs at low plasma density regime, compared to results from the uncompensated Langmuir probes. This method can also provide real-time tuning and thus, high quality EEPF measurement is possible even when the rf discharge condition is changed.

GT1 33 Experimental investigation of plasma parameter profiles on wafer level with discharge gap lengths in an inductively coupled plasma JU HO KIM, *Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea* YOUNG-CHEOL KIM, JUNE YOUNG KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University, Seoul 133-791, South Korea* CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea* Experimental investigation of the gap length effect on plasma parameters was performed in a planar type inductively coupled plasma (ICP) at various conditions. The spatial profile (wafer level, 260 mm) of ion flux, and electron temperature were measured from a 2-D floating probe measurement system. At low pressures, the spatial profile of the ion flux rarely changed; however, at relatively high pressures, the spatial profile of the ion flux dramatically changed with different discharge gap length.

GT1 34 Inductively-coupled plasmas in pure O_2: measurements of densities of O atoms, electrons and vibrationally excited Omolecules MICKAËL FOUCHER, *LPP-CNRS UMR*

7648 EMILE CARBONE, *CEA grenoble* JEAN-PAUL BOOTH, PASCAL CHABERT, *LPP-CNRS UMR 7648* LPP-PLASMAS FROIDS TEAM Inductively-coupled plasmas containing O_2 (pure or mixtures) are widely used in materials processing. Various simulations have been developed but experimental validation is still sparse. We present here a comprehensive data set for O_2 plasmas over a wide range of pressure and RF power to address this need. The plasma is excited with a 4-turn planar coil through a dielectric window at 13.56 MHz in an anodized aluminium reactor. The electron density was measured with a microwave resonator hairpin probe. It increases continuously with RF power, but with pressure it passes through a broad maximum around 40 mTorr. Ground-state O atom densities were determined using Two-Photon Absorption Laser-Induced Fluorescence combined with absolute calibration using Xe TALIF. The atom density increases with gas pressure, but with RF power it first increases but progressively saturates tot about 20% of the initial (no plasma) gas density. A novel high-sensitivity ultra-broad-band absorption spectroscopy setup allowed O_2 molecules to be detected in high vibrational states (up to $v = 18$) via the Schumann-Runge bands. Molecular Ovibrational temperatures up to 12,000 K were observed, whereas the rotational temperature did not exceed 500 K. This indicates that electron-impact pumping of vibrational levels is important, whereas V-T transfer is slow. These processes must be included to accurately model the O_2 plasma system.

GT1 35 Study on self-bias effect in floating probe using dual frequency IL-SEO PARK, HYO-CHANG LEE, YU-SIN KIM, *Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea* DONG-HWAN KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University, Seoul, 133-791, Republic of Korea* CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea* A floating probe is one of the promising electrical probe for plasma diagnostics, which is using small sinusoidal signal to perturb the plasma for obtaining plasma parameters such as ion flux and electron temperature. The ac signal could be selected for the purpose of the plasma condition and its advantages, and single or dual frequency is usually used for diagnostics. When one or dual frequency is applied to the probe, a self-bias effect is observed in the capacitor in series to the floating probe. Due to the mobility difference of the ions and electrons, the self-bias effect is presented at the capacitor. In this paper, two consecutive frequencies are applied to the probe with phase differences. The result of the self-bias effect agrees with the floating probe theory, which gives a relation among electron temperature, phase difference and amplitude of the each frequency. The electron temperatures by using the relation can be obtained, and it agree with those of a Langmuir probe.

GT1 36 Measurement of the surface charge accumulation using anodic aluminum oxide(AAO) structure in an inductively coupled plasma JI-HWAN PARK, SEUNG-JU OH, HYO-CHANG LEE, YU-SIN KIM, YOUNG-CHEOL KIM, JUNE YOUNG KIM, *Hanyang University* CHANG-SEOUNG HA, *SEMES* SOON-HO KWON, JUNG-JOONG LEE, *Seoul University* CHIN-WOOK CHUNG, *Hanyang University* As the critical dimension of the nano-device shrinks, an undesired etch profile occurs during plasma etch process. One of the reasons is the local electric field due to the surface charge accumulation. To demonstrate the surface charge accumulation, an anodic aluminum oxide (AAO) membrane which has high aspect ratio is used. The potential difference between top electrode and bottom electrode in an anodic aluminum oxide contact structure is measured during inductively coupled plasma exposure. The voltage difference is changed with external discharge conditions, such as gas pressure, input power, and gas species and the result is analyzed with the measured plasma parameters.

GT1 37 The effect of rf plasma fluctuation on floating harmonic probes JAEWON LEE, KYUNGHYUN KIM, SANGBUM JEON, CHIN-WOOK CHUNG, *Hanyang University* Measurement of electron temperature, plasma density and ion flux with floating harmonic method (FHM) has several advantages for RF plasma diagnosis. In principle, RF oscillation of plasma does not distort the characteristic of the probe at a floating potential. Thus, an active or passive RF compensation is unnecessary. However, in fact, the uncompensated probe results in higher electron temperature than the rf compensated probe especially at low plasma density. Plasma parameters from the FHM and that of Langmuir probe was compared, and it shows that the measured plasma parameter from RF compensated floating probe (FHM) has great agreements with Langmuir probe.

GT1 38 In-situ measurement method of sheath capacitance in plasmas JIN-YONG KIM, CHIN-WOOK CHUNG, *Hanyang Univ.* In-situ measurement method of sheath capacitance was studied. To measure the sheath capacitance, small dual frequency sinusoidal voltage signals ($\sim$1 V) are applied to floating planar probe. The sheath circuit model and capacitance of the dielectric deposition film on the probe are considered in our measurement. The experiment was performed at various discharge conditions and our results are in good agreements with other studies. This study can be helpful for plasma monitoring in industrial processing.

GT1 39 Two-photon laser-induced fluorescence imaging of atomic oxygen in an atmospheric pressure plasma jet JACOB SCHMIDT, *Spectral Energies, LLC.* BRIAN SANDS, *UES, Inc.* WARUNA KULATILAKA, SUKESH ROY, *Spectral Energies, LLC.* JAMES SCOFIELD, JAMES GORD, *Air Force Research Laboratory* A femtosecond two-photon absorption laser-induced fluorescence (fs-TALIF) diagnostic is applied to a nanosecond-pulsed, capillary dielectric barrier discharge (CDBD) plasma jet flowing helium with a variable oxygen admixture to produce two-dimensional images of atomic oxygen distributions. The high-peak intensity, low-average energy fs pulses, combined with increased spectral bandwidth, increase the number of photon pairs responsible for the two-photon excitation, resulting in increased TALIF signal. These features enabled imaging of absolute atomic oxygen number densities ranging from 4.07×10^{15} cm^{-3}, to the single-shot detection limit of 10^{12} cm^{-3}. Atomic oxygen imaging results are compared against traditional nanosecond diagnostics employing the same two-photon excitation scheme, including issues of experimental error, signal strengths, and quenching. Xenon calibration is used for quantification of the fluorescence signal. Imaging results show this CDBD capable of remotely generating quasi-steady-state atomic oxygen densities with a spatial distribution that depends on oxygen admixture.

GT1 40 High sensitivity ultra-broad-band absorption spectroscopy applied to inductively-coupled plasmas in Cl/O MICKAËL FOUCHER, *LPP-CNRS UMR 7648* EMILE CARBONE, *CEA grnoble* JEAN-PAUL BOOTH, PASCAL CHABERT, *LPP-CNRS UMR 7648* LPP-PLASMAS FROIDS TEAM Broad-band absorption spectroscopy is a powerful diagnostic for reactive plasmas, allowing measurement of the absolute densities of numerous atoms, molecules and free radicals in ground and various excited states. Previously Xe arc lamps have been used as the continuum light source, but these suffer from spatiotemporal fluctuations which limit the sensitivity to about 10^{-3} in absorption. More recently UV light-emitting diodes have been used, but these only emit over a very limited spectral range. Our new absorption spectroscopy setup uses a laser-driven plasma light source, achromatic optics and an aberration free spectrograph. This light source has ideal characteristics for absorption spectroscopy (high intensity, stability and a wide spectral range (200–1000 nm)), overcoming previous limitations. Noise levels as low as 10^{-5} can be achieved in single-pass absorption, covering up to 250 nm in a single spectrum. Measurements were made in a 13.56 MHz inductively-coupled plasma reactor in O, Cl and Cl/O mixtures. We observed absorption by Cl, O and ClxOy molecules, and excited state atoms. Whereas the Clvibrational distribution is close to equilibrium with the gas translational temperature, Omolecules show high vibrational excitation (up to $v = 18$, T_{vib}12,000 K). However, high resolution spectra of O indicated rotational temperatures up to only 500 K. Many oxychloride molecules were detected in Cl/O mixtures.

GT1 41 Hairpin resonator probes with frequency domain boxcar operation for time resolved density measurements in pulsed RF discharges DAVID PETERSON, THERESA KUMMERER, *North Carolina State University* DAVID COUMOU, *MKS Instruments, ENI Power Division, Rochester NY* STEVEN SHANNON, *North Carolina State University* In this work, microsecond time resolved electron density measurements in pulsed RF discharges are shown using an automated hairpin resonance probe using relatively low cost electronics, on par with normal Langmuir probe boxcar mode operation. A low cost signal generator is used to produce the applied microwave frequency and the reflected waveform is filtered to remove the RF component. The signal is then heterodyned with a simple frequency mixer to produce a dc signal read by an oscilloscope to determine the electron density. The applied microwave frequency is automatically shifted in small increments in a frequency boxcar routine through a Labview^{TM}program to determine the resonant frequency. A simple dc sheath correction is then easily applied since the probe is fully floating, producing low cost, high fidelity, and highly reproducible electron density measurements. The measurements are made in a capacitively coupled, parallel plate configuration in a 13.56 MHz, 50–200 W RF discharge pulsed at 500 Hz, 200 W, 50% duty cycle. The gas input ranged from 50–100 mTorr pure Ar or with 5–10% O/He mixtures.

GT1 42 Experimental Characterization of the Time-Averaged and Oscillatory Behavior of a Hall Plasma Discharge* CHRISTOPHER YOUNG, ANDREA LUCCA FABRIS, NICOLAS GASCON, MARK CAPPELLI, *Stanford University* An extensive experimental campaign characterizes a 70 mm diameter stationary plasma thruster operating on xenon in the 200–500 W power range. This study resolves both time-averaged properties and oscillatory phenomena in the plasma discharge. Specifically, we explore the time variation of the plume ion velocity field referenced to periodic discharge current oscillations using time-synchronized laser induced fluorescence (LIF) measurements. This LIF scheme relies on a triggered signal acquisition gate locked at a given phase of the current oscillation period. The laser is modulated at a characteristic frequency and homodyne detection through a lock-in amplifier extracts the induced fluorescence signal out of the bright background emission.

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

GT1 43 Periodic Evolution of a Xe I Population in an Oscillatory Discharge Captured Through Time-Synchronized Laser Induced Fluorescence Techniques* ANDREA LUCCA FABRIS, CHRISTOPHER YOUNG, MARK CAPPELLI, *Stanford University* We track the evolution of the Xe I $6s'\,[1/2]_1 - 6p'\,[3/2]_2$ (834.68 nm air) transition lineshape in a plasma discharge oscillating at 60 Hz. Two time-synchronized laser induced fluorescence techniques based on phase sensitive detection of the fluorescence signal are demonstrated, yielding consistent results. One approach used previously involves a sample-and-hold procedure that collects fluorescence signal at a particular phase in the oscillation period and holds the average value until the following sample. The second method is based on fast switching of the fluorescence signal; only the signal collected inside the acquisition gate is sent to a lock-in amplifier for processing. Both methods rely on modulating the exciting laser beam and the latter permits operation at a much higher frequency range with reduced spectral noise density. The maximum observed peak fluorescence intensity occurs at low discharge currents, although the peak intensity drops to zero at zero discharge current. The peak intensity also decreases at the discharge current maximum. Time-varying properties of the xenon neutrals are extracted from a lineshape analysis.

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

GT1 44 Theoretical modeling of laser-induced plasmas using the ATOMIC code* JAMES COLGAN, HEATHER JOHNS, DAVID KILCREASE, ELIZABETH JUDGE, JAMES BAREFIELD II, SAMUEL CLEGG, KYLE HARTIG, *Los Alamos National Laboratory* We report on efforts to model the emission spectra generated from laser-induced breakdown spectroscopy (LIBS). LIBS is a popular and powerful method of quickly and accurately characterizing unknown samples in a remote manner. In particular, LIBS is utilized by the ChemCam instrument on the Mars Science Laboratory. We model the LIBS plasma using the Los Alamos suite of atomic physics codes. Since LIBS plasmas generally have temperatures of somewhere between 3000 K and 12000 K, the emission spectra typically result from the neutral and singly ionized stages of the target atoms. We use the Los Alamos atomic structure and collision codes to generate sets of atomic data and use the plasma kinetics code ATOMIC to perform LTE or non-LTE calculations that generate level populations and an emission spectrum for the element of interest. In this presentation we compare the emission spectrum from ATOMIC with an Fe LIBS laboratory-generated plasma as well as spectra from the ChemCam instrument. We also discuss various physics aspects of the modeling of LIBS plasmas that are necessary for accurate characterization of the plasma, such as multi-element target composition effects, radiation transport effects, and accurate line shape treatments.

*The Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. DE-AC5206NA25396.

GT1 45 RF Models for Plasma-Surface Interactions in VSim* THOMAS G. JENKINS, D.N. SMITHE, A.Y. PANKIN, C.M. ROARK, C.D. ZHOU, P.H. STOLTZ, S.E. KRUGER, *Tech-X*

Corporation An overview of ongoing enhancements to the Plasma Discharge (PD) module of Tech-X's VSim software tool is presented. A sub-grid kinetic sheath model, developed for the accurate computation of sheath potentials near metal and dielectric-coated walls, enables the physical effects of DC and RF sheath physics to be included in macroscopic-scale plasma simulations that need not explicitly resolve sheath scale lengths. Sheath potential evolution, together with particle behavior near the sheath, can thus be simulated in complex geometries. Generalizations of the model to include sputtering, secondary electron emission, and effects from multiple ion species and background magnetic fields are summarized; related numerical results are also presented. In addition, improved tools for plasma chemistry and IEDF/EEDF visualization and modeling are discussed, as well as our initial efforts toward the development of hybrid fluid/kinetic transition capabilities within VSim. Ultimately, we aim to establish VSimPD as a robust, efficient computational tool for modeling industrial plasma processes.

*Supported by US DoE SBIR-I/II Award DE-SC0009501.

GT1 46 Electrical characteristics and energy budget of dielectric barrier discharges in argon at atmospheric pressure* MARKUS M. BECKER, TOMAS HODER, DETLEF LOFFHAGEN, *INP Greifswald* Recently, an asymmetric dielectric barrier discharge ignited in atmospheric pressure argon in a single filament configuration has been analysed by experiments and modelling [1,2]. A special feature of the discharge under consideration is the occurrence of two different discharge modes at different amplitudes of the sinusoidal voltage supply. At voltages below the critical voltage of 2 kV ordinary filamentary discharges occur, while at higher voltages discharges with striated filaments emerge. In the present contribution the mode transition is investigated with respect to the electrical characteristics as well as the electron energy budget by means of numerical modelling. It is found that the mode transition caused by an increase of the voltage amplitude is accompanied by a non-linear change of the power density and a marked rise of the electron energy gain in chemo-ionization processes.

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

[1]T. Hoder *et al.*, Phys. Rev. E **84**, 46404 (2011).
[2]M. M. Becker *et al.*, J. Phys. D: Appl. Phys. **46**, 355203 (2013).

GT1 47 Modeling of filaments and gas flow in an atmospheric pressure plasma jet* FLORIAN SIGENEGER, DETLEF LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* A non-thermal atmospheric pressure plasma jet is investigated by a combination of different approaches. The jet consists of two concentric capillaries and two ring-shaped electrodes which are twisted around the outer capillary to supply the rf power at 27.12 MHz. One part of the model is devoted to describe one single filament as observed in the active volume between the electrodes. For this purpose a two-dimensional axisymmetric fluid model has been used which comprises continuity equations for electrons and the most important argon species, the electron energy balance equation, Poisson's equation and an equation for the surface charges at the walls of the capillaries. Furthermore, the heat balance equation is solved to determine the temperature of the gas. The inclusion of contraction mechanisms allows to describe the establishment of a constricted filament and even pronounced striations as observed in the experiments. The second part uses results of the first one to model the gas flow through the jet under the influence of local heating at the position of the filament which leads finally to an azimuthal rotation of the filaments as observed in experiments.

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

GT1 48 Fast 2D Fluid-Analytical Simulation of IEDs and Plasma Uniformity in Multi-frequency CCPs* E. KAWAMURA, M.A. LIEBERMAN, D.B. GRAVES, *Univ of California - Berkeley* A fast 2D axisymmetric fluid-analytical model using the finite elements tool COMSOL is interfaced with a 1D particle-in-cell (PIC) code to study ion energy distributions (IEDs) in multi-frequency argon capacitively coupled plasmas (CCPs). A bulk fluid plasma model which solves the time-dependent plasma fluid equations is coupled with an analytical sheath model which solves for the sheath parameters. The fluid-analytical results are used as input to a PIC simulation of the sheath region of the discharge to obtain the IEDs at the wafer electrode. Each fluid-analytical-PIC simulation on a moderate 2.2 GHz CPU workstation with 8 GB of memory took about 15–20 minutes. The 2D multi-frequency fluid-analytical model was compared to 1D PIC simulations of a symmetric parallel plate discharge, showing good agreement. Fluid-analytical simulations of a 2/60/162 MHz argon CCP with a typical asymmetric reactor geometry were also conducted. The low 2 MHz frequency controlled the sheath width and voltage while the higher frequencies controlled the plasma production. A standing wave was observable at the highest frequency of 162 MHz. Adding 2 MHz power to a 60 MHz discharge or 162 MHz to a dual frequency 2 MHz/60 MHz discharge enhanced the plasma uniformity.

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

GT1 49 Transport Parameters of $F^{(-)}$ Ions in Mixtures Ar/BF_3* ZELJKA NIKITOVIC, VLADIMIR STOJANOVIC, ZORAN RASPOPOVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade* JASMINA JOVANOVIC, *Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11000 Belgrade, Serbia* ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade* Transport parameters of $F^{(-)}$ ions in mixtures Ar/BF_3 in DC fields were calculated by using Monte Carlo simulation technique. The scattering cross-section set for $F^{(-)}$ in BF_3 is assembled on the basis of Nanbu's technique separating elastic from reactive collisions. In this work we present transport coefficients for the conditions of low and moderate reduced electric fields E/N (E-electric field, N-gas density) accounting for the non-conservative collisions. This mixture is usual in plasma etching applications.

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

GT1 50 The Influence of Anode Size on Bulk Plasma State: Simulation, Theory, and Experiment* MATTHEW HOPKINS, BENJAMIN YEE, EDWARD BARNAT, *Sandia National Laboratories* SCOTT BAALRUD, *University of Iowa* We present recent PIC modeling results in pursuit of identifying the relationship between bulk plasma characteristics and a biased anodic surface. In the limit of small anode size we expect the anode to operate as an ideal probe and exhibit no significant influence on the bulk plasma state.

In the other limit of a large anode size we expect the bulk plasma to "lock" onto the anode potential and the plasma state to be heavily influenced by the anode potential. Our investigations include the plasma-anode interface (sheath) structure, plasma potential, and plasma electron energy distribution function modification. The basis for our investigation lies in the plasma-anode interface model from Baalrud *et al.* [1] In particular, we target the transition from ion-rich sheaths to electron-rich sheaths at the anode. The theoretical model predicts a transition as a function of the anode-to-wall area ratio, A_A/A_W. Comparisons are made between the simulation model, theoretical model, and experimental results. Considerations specific to modeling are also presented.

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

[1]Baalrud, Hershkowitz, and Longmier, Phys. Plasmas **14**, 014109 (2007).

GT1 51 A kinetic electron-neutral collision model for particle-in-cell plasma simulation* TIMOTHY POINTON, KEITH CARTWRIGHT, *Sandia National Laboratories* Details of a kinetic electron-neutral collision model for particle-in-cell plasma simulation codes are presented. The model uses an efficient scheme to randomly select collision events – elastic, excitation and ionization – with the appropriate probability [1] Ionization events create electron-ion pairs, and the secondary electrons can themselves ionize the gas. To maintain a manageable particle count, a particle merger algorithm can be used to periodically replace all particles of a given species in a cell with a new, smaller set that conserves charge, momentum, and energy [2] Small-scale tests show that results with the merger are in good agreement with non-merged runs. Large simulations can only be done with the merger on, and typically show excellent merger efficiency (>90%).

*Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the U.S. DOE's NNSA under Contract DE-AC04-94-AL85000.

[1]H. Sugawara *et al.*, J. Comput. Phys. **223**, 298 (2007).
[2]D. R. Welch *et al.*, J. Comput. Phys. **227**, 143 (2007).

GT1 52 Numerical simulation of capacitively coupled RF plasma flowing through a tube for the synthesis of silicon nanocrystals* ROMAIN LE PICARD, *University of Minnesota* SANG-HEON SONG, *University of Michigan* DAVID PORTER, *Minnesota Supercomputing Institute* MARK KUSHNER, *University of Michigan* STEVEN GIRSHICK, *University of Minnesota* Silicon nanocrystals (SiNCs) are of interest for applications in the photonics, electronics, and biomedical areas. Nonthermal plasmas offer several potential advantages for synthesizing SiNCs. In this work, we have developed a numerical model of a capacitively coupled RF plasma used for the synthesis of SiNCs. The plasma, consisting of silane diluted in argon at a total pressure of about 2 Torr, flows through a narrow quartz tube with two ring electrodes. The numerical model is 2D, assuming axisymmetry. An aerosol sectional model is added to the Hybrid Plasma Equipment Model developed by Kushner and coworkers. The aerosol module solves for aerosol size distributions and size-dependent charge distributions. A detailed chemical kinetic mechanism considering silicon hydride species containing up to 5 Si atoms is used to model particle nucleation and surface growth. The sectional model calculates coagulation, particle transport by electric force, neutral drag and ion drag, and particle charging using orbital motion limited theory. Simulation results are presented for selected operating conditions, and are compared to experimental results.

*This work was partially supported by the US Dept. of Energy Office of Fusion Energy Science (DE-SC0001939), the US National Science Foundation (CHE-124752), and the Minnesota Supercomputing Institute.

GT1 53 Numerical optimization of collisional cross sections for plasma simulation by Broyden-Fletcher-Goldfarb-Shanno method SANG-YOUNG CHUNG, DEUK-CHUL KWON, MI-YOUNG SONG, JUNG-SIK YOON, *National Fusion Research Institute* For reliable plasma simulation an accurate full-set data of collision cross sections between each species participated in the plasma is required. However, the full-set of the reaction data is hard to achieve and estimated data have been used for the missing. To achieve reliable reaction data researchers have tuned the estimated reaction data so that the simulation results with the data agree with experimental results. However, as the number of data to be tuned is increased it becomes very hard work for researchers. In this study, we developed a code to optimize the data numerically based on the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm and adopted with a 0-dimensional global simulator for semiconductor processing plasma. BFGS algorithm is a type of a quasi-Newton method. The second derivatives are used for a next estimation like Newton method but are calculated by iterations from first derivatives and previous second derivatives. So the function is called (i.e. the simulator is executed) much smaller times than Newton method. Parallel algorithm was applied to the code to save time. In the serial code the calculation time for each iteration were proportional to the number of unknown variables but it became independent of the number of the variables in the parallel code.

GT1 54 Transport Properties of Negative Ions in HBR Plasmas VLADIMIR STOJANOVIC, *Institute of Physics, University of Belgrade, P.O. Box 68, 11080 Belgrade, Serbia* NENAD IVANOVIC, *Vinca Institute for Nuclear Science, University of Belgrade, P.O. Box 522, 11000 Belgrade, Serbia* MARIJA RADMILOVIC-RADJENOVIC, ZORAN RASPOPOVIC, ALEKSANDAR BOJAROV, ZORAN PETROVIC, *Institute of Physics, University of Belgrade, P.O. Box 68, 11080 Belgrade, Serbia* Low temperature plasma in halogenated gases is standard environment for dry etching of semiconductors. Amount of negative ions in HBr plasmas determines electronegativity so modeling etching devices requires data for anion transport properties. In this work we present cross section set for Br^- ions in HBr assembled by using Denpoh-Nanbu theory [1]. The threshold energy values were calculated by known heats of formation. The calculated total cross section accounts for ion-induced-dipole and ion-permanent-dipole interaction by using the local-dipole model. The total cross section was corrected to fit the reduced mobility obtained by SACM (Statistical Adiabatic Channel Model) approximation. Existing cross section measurements [2] were used to scale calculated cross sections. Finally, we used Monte Carlo method to determine transport parameters for Br^- as a function of reduced electric fields that can be *used in fluid and hybrid* plasma models.

[1]K. Denpoh and K. Nanbu, J. Vac. Sci. Technol. A **16**, 1201 (1998).
[2]R. L. Champion, L. D. Doverspike, M. S. Huq, D. Scott, and Y. Wang, J. Chem. Phys. **88**, 5475 (1988).

GT1 55 Extended dielectric relaxation scheme for fluid transport simulations of high density plasma discharges* DEUK-CHUL KWON, MI-YOUNG SONG, JUNG-SIK YOON, *Natl*

Fusion Res Inst It is well known that the dielectric relaxation scheme (DRS) can efficiently overcome the limitation on the simulation time step for fluid transport simulations of high density plasma discharges. By imitating a realistic and physical shielding process of electric field perturbation, the DRS overcomes the dielectric limitation on time step. However, the electric field was obtained with assuming the drift-diffusion approximation. Although the drift-diffusion expressions are good approximations for both the electrons and ions at high pressure, the inertial term cannot be neglected in the ion momentum equation for low pressure. Therefore, in this work, we developed the extended DRS by introducing an effective electric field. To compare the extended DRS with the previous method, two-dimensional fluid simulations for inductively coupled plasma discharges were performed.

*This work was supported by the Industrial Strategic Technology Development Program (10041637, Development of Dry Etch System for 10 nm class SADP Process) funded by the Ministry of Knowledge Economy (MKE, Korea).

GT1 56 PLASIMO model of micro-plasma jet for biomedical applications DIANA MIHAILOVA, ANA SOBOTA, WOUTER GRAEF, JAN VAN DIJK, *Eindhoven University of Technology* GERJAN HAGELAAR, *CNRS, University of Toulouse* Non-equilibrium atmospheric pressure micro-plasma jets are widely studied for use in biotechnology, including treatment of human tissue. The setup under study consists of capillary powered electrode through which helium gas flows and a grounded ring electrode placed a distance of few mm in front of the capillary. The discharge is excited by sinusoidal voltage with amplitude of 2 kV and 30 KHz repetition rate. The plume emanating from the jet, or the plasma bullets, propagates through a Pyrex tube and the gas phase channel of helium into the surrounding air.aim of this work is to get insight into the plasma constituents that can affect directly or indirectly living tissue. This includes radicals (OH, NO, O,), ions and electrons, UV radiation, electrical fields. PLASIMO modelling toolkit is used to simulate the capillary plasma-jet in order to quantify the delivery of fluxes and fields to the treated tissue. Verification is made by comparing results obtained with the PLASIMO and MAGMA codes (developed at LAPLACE, Toulouse) for the same input specifications. Both models are validated by comparison with experimental observations at various operating parameters.

GT1 57 Fluid model of magnetic drifts and instabilities in magnetized low-temperature plasma sources* GERJAN HAGELAAR, ROMAIN FUTTERSACK, ROMAIN BAUDE, *LAPLACE, CNRS and University of Toulouse* This paper presents a self-consistent fluid model of low-temperature plasma transport across a magnetic field, designed in particular to describe magnetic drifts and instabilities in the plane perpendicular to the field lines. The model is based on electron and ion continuity equations and full momentum equations and an electron energy equation, without a priori assumptions on the ordering of physical scales (Larmor radii, mean free paths, geometrical dimensions) so that it can cover a wide range of conditions, from non-magnetized collisional plasmas to tokamak edge plasmas. The model is applied to different basic configurations of immediate interest for applications such as ion negative sources. We show that in a typical magnetic filter configuration (e.g. in the ITER negative ion source or Pegases thruster), the magnetic drift is obstructed by the chamber walls which induces an asymmetric electron flux across the filter, scaling as 1/B. These results have been confirmed by experimental data from an in-house laboratory set-up. We also present model results on the Cybele ion source featuring a magnetized plasma column, in which the transport is governed by rotating instabilities and very sensitive to the boundary conditions at the end of the column.

*This work is supported by French National Research Agency (Project METRIS ANR-11-JS09-008).

GT1 58 Propagation of a positive streamer discharge along a dielectric rod* ANNA DUBINOVA, UTE EBERT, JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica* We simulate positive streamer discharges developing in artificial air near dielectric and conductive materials. This research is important, for example, in the high voltage technology where surface flashovers are to beavoided. We designed an axially symmetric model in which a positive streamer develops at the tip of the needle electrode (parameterized as a spheroid) and propagates towards and then along a dielectric rod (a cylinder). Our model includes field modification due to the polarization effect, photoionization, charge accumulation on the dielectric surface and photoelectron emission. We describe a numerical method (a generalized Ghost Fluid Method) which allowed us to include dielectric interfaces into our streamer model, in an accurate and fast manner. Finally, we measure the velocity of a positive streamer propagating along the dielectric rod and compare it with experiments. We discuss the importance of the surface photoelectron emission as an intrinsically non-local source of free electrons for streamer propagation.

*The work is supported by the STW Project 12119, partly funded by ABB.

GT1 59 Modeling DC-circuit-breakers for long distance electricity transmission ASHUTOSH AGNIHOTRI, *Centrum Wiskunde en Informatica, Amsterdam* UTE EBERT, *Centrum Wiskunde en Informatica, Amsterdam & Eindhoven University of Technology, Eindhoven* WILLEM HUNDSDORFER, *Centrum Wiskunde en Informatica, Amsterdam & Radboud University, Nijmegen* Modeling a circuit-breaker is a multiple timescale problem which involves a cascade of physical processes from avalanche phase to streamer, spark and post discharge phase, with a transition phase between each pair of processes. In particular, Jin Zhang and Bert van Heesch at Eindhoven University of Technology investigate now whether the conventional SF6 can be replaced by supercritical nitrogen. We focus on modeling space charge effects, gas heating and secondary electron emission from cathode. We develop a two-dimensional drift-diffusion model for streamers coupled to the Euler equations for the gas to study the related phenomena. We perform simulations to capture thermal shocks and induced pressure waves caused by the electrical breakdown of the surrounding gas. We include heat exchange mechanisms between the electrons/ions and the surrounding gas.

GT1 60 2D streamer simulations using the high order fluid model ARAM MARKOSYAN, *University of Michigan* SASHA DUJKO, *University of Belgrade* UTE EBERT, *CWI* In 1D, the recently derived high order fluid model [1] shows promising performance and accuracy compared to the classical first order model using the local field approximation [2]. Here we simulate cylindrically symmetric streamers between two planar electrodes with the high order fluid model. The system is discretized using finite volume spatial discretization (high-resolution scheme) and explicit time stepping. We discuss the results and compare with previous work.

[1]Dujko *et al.*, J. Phys. D **46**, 5202 (2013).
[2]Markosyan *et al.*, J. Phys. D **46**, 5203 (2013).

GT1 61 Simulating the inception of pulsed discharges around needle electrodes* JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica, The Netherlands* SHE CHEN, *Tsinghua University, China* LUUK HEIJMANS, *Eindhoven University of Technology, The Netherlands* RONG ZENG, *Tsinghua University, China* SANDER NIJDAM, *Eindhoven University of Technology, The Netherlands* UTE EBERT, *Centrum Wiskunde & Informatica and Eindhoven University of Technology, The Netherlands* When a positive voltage pulse is applied to a sharp electrode, an *inception cloud* can form around the electrode tip. This is an almost spherically expanding ionized region. As recently demonstrated in experiments by S. Chen, L. Heijmans and S. Nijdam, the properties of these inception clouds depend on the gas mixture and on the voltage pulse. We present a 3D particle model to simulate the initial stage of pulsed discharges near needle electrodes. With this model, we investigate how the properties of inception clouds (growth velocity, maximum size, time of destabilization) depend on the gas mixture and voltage pulse, and we compare with the experiments mentioned above.

*J.T. was supported by STW Project 10755, S.C. by China Scholarship Council 201306210141.

GT1 62 Application of ILDM Technique for Simplifying Complex Plasma Chemistry* TAFIZUR REHMAN, KIM PEERENBOOM, EFE KEMANECI, WOUTER GRAEF, JAN VANDIJK, *Eindhoven University of Technology* Complete numerical description of plasma involves solving complex set of space and time dependent conservation and rate equations. Solution of this large set of equations induces a high computational load on the system. Combustion research is another branch of science that deals with the same issue. To overcome the difficulty, combustion community employs various Chemical Reduction Techniques(CRT). The CRT simply uses the fact that, due to wildly varying time scales, reaction system is not evenly sensitive to all the reactions but some reactions are fast and attain steady state in short interval of time. Hence, fast time scale variation becomes less important and the full description of the system can be given by the slow time scales without any significant loss in chemical kinetics description. The chemical reduction technique we employed is ILDM (Intrinsic Low Dimensional Manifold). This technique finds the low dimensional space inside a complete state space such that after a short interval of time the fast time scales of the system will quickly move onto this low dimensional manifold and the full system description can be given by this lower dimensional manifold. One can use these techniques of combustion research to simplify the complex chemistry in plasma simulation.

*This project is supported by Shell-FOM program (Project No. 12CS087).

GT1 63 Parametric calculations of plasma jets generated by microdischarges* M. FOLETTO, *Univ Toulouse* J.P. BOEUF, L.C. PITCHFORD, *CNRS and Univ Toulouse* "Guided streamers" or "plasma jets" can be generated in open air by applying rf or impulse voltages to a microdischarge through which there is a flow of helium. For flow conditions such that a helium column surrounded by air extends some distance (centimeters) past the exit of the microdischarge, a plasma jet can be initiated. Previous works have shown that this is essentially a streamer propagating in the easily-ionized helium column and impeded from branching by the surrounding air. For many applications, it is of interest to understand the parameters controlling the properties of the plasma jet. To this end, we present results from a series of parametric calculations using our previously published model [1] to identify the influence of the microdischarge configuration on the generation, propagation, and properties of the plasma jet. We focus mainly on a geometry with hollow, concentric electrodes separated by a dielectric tube corresponding to the experiments of Douat *et al.* [2], and we vary the dimensions and relative off-set of the electrodes, applying an impulse voltage or the experimental waveform to the inner electrode. For the same applied voltage waveform, parameters which influence the electric field and electron density in the plasma jet are the dielectric permittivity, the tube diameter, and the dielectric length.

*Support by the French National Research Agency project PAMPA.

[1]J. P. Boeuf *et al.*, J. Phys. D: Appl. Phys. **46**, 015201 (2013).
[2]C. Douat *et al.*, Plasma Sources Sci. Technol. **21**, 034010 (2012).

GT1 64 A PLASIMO global model for plasma assisted CO_2 conversion WOUTER GRAEF, TAFIZUR REHMAN, DIANA MIHAILOVA, JAN VAN DIJK, *Eindhoven University of Technology* Conversion of CO_2 has become a major challenge of our time as it is of interest for the reduction of greenhouse gases in our atmosphere, but also to store energy thereby relieving the supply and demand discrepancy of many alternative forms of energy. Plasma assisted CO_2 conversion is heavily investigated as an efficient method to achieve this goal. Numerical modeling is an important aspect of this investigation, but is difficult due to the complex chemistry. A global model has been constructed to focus on the CO_2 chemistry including its vibrational kinetics. The model has been realized using the global model module of PLASIMO, a highly modular plasma modeling framework. It is based on another model [1] that was constructed using the well-established code Global_kin. The aim of the model is therefore twofold. First, to study the chemistry and identify the most important species and reactions and perform parametric studies. The knowledge gained can be applied to other, spatially resolved models. Second, by implementing the same chemistry in the two different global model codes, a cross validation can be performed, a vital scientific process often overlooked in practice.

[1]Tomáš Kozák and Annemie Bogaerts, submitted to Plasma Sources Sci. Tech.

GT1 65 Magneto-hydrodynamic simulation of hypervelocity neutral plasma jets and their interactions with materials generating extreme conditions VIVEK SUBRAMANIAM, LAXMINARAYAN RAJA, *The University of Texas at Austin* HARISWARAN SITARAMAN, *None* The development of a Magneto-hydrodynamics (MHD) numerical tool to study high density thermal plasma in a co-axial plasma gun is presented. The MHD governing equations are numerically solved using a matrix free implicit scheme in an unstructured grid finite volume framework. The MHD model is used to characterize the high energy jet which emanates from the accelerator. The solver is then used to predict the conditions created at the surface of a flat plate placed at a fixed distance from the exit of the gun. The model parameters are adjusted so that the energy density of the jet impacting the plate is of the same order of magnitude as that of the Edge Localized Mode (ELM) disruptions in thermonuclear fusion reactors. The idea is to use the pressure and temperature on the plate surface to obtain an estimate of the stress created on the plate due to jet impact. The model is used to quantify damage caused by ELM disruptions on the confining material surface.

[1]H. Sitaraman and L. L. Raja, Phys. Plasmas **21**, 012104 (2014).

GT1 66 Computational modelling of plasma control using electron injection from electrode surfaces PREMKUMAR PANNEERCHELVAM, LAXMINARAYAN RAJA, *The University of Texas at Austin* A common property of gamma-mode discharge is the importance of electron emission from surfaces in establishing the overall discharge structure. The secondary electron emission (SEE) from the cathode surface plays a key role in sustaining direct current glow discharges. Active control of SEE could be used to realize control over discharge properties. Chen and Eden [1] control surface electron emission in a tri-electrode microdischarge to realize gain properties in a plasma transistor device. This work discusses a computational model of a plasma transistor microdischarge device. It includes description of active surface electron emission from one of the electrode surfaces. Gain properties in the plasma by controllable injection of electrons from the surface is shown. The non-linear processes in the plasma that realize rapid increase in the plasma density and current as a function of the electron injection from the electrode is studied using the model.

[1]K. F. Chen and J. G. Eden, Appl. Phys. Lett. **93**, 161501 (2008).

GT1 67 Validation of RF CCP Discharge Model against Experimental Data using PIC Method* CASEY ICENHOUR, THERESA KUMMERER, *North Carolina State University* DAVID L. GREEN, *Oak Ridge National Laboratory* DAVID SMITHE, *Tech-X Corporation* STEVEN SHANNON, *North Carolina State University* The particle-in-cell (PIC) simulation method is a well-known standard for the simulation of laboratory plasma discharges. Using parallel computation on the Titan supercomputer at Oak Ridge National Laboratory (ORNL), this research is concerned with validation of a radio-frequency (RF) capacitively-coupled plasma (CCP) discharge PIC model against previously obtained experimental data. The plasma sources under simulation are 10–100 mTorr argon plasmas with a 13 MHz source and 27 MHz source operating at 50–200 W in both pulse and constant power conditions. Plasma parameters of interest in the validation include peak electron density, electron temperature, and RF plasma sheath voltages and thicknesses. The plasma is modeled utilizing the VSim plasma simulation tool, developed by the Tech-X Corporation. The implementation used here is a two-dimensional electromagnetic model, with corresponding external circuit model of the experimental setup. The goal of this study is to develop models for more complex RF plasma systems utilizing highly parallel computing technologies and methodology.

*This work is carried out with the support of Oak Ridge National Laboratory and the Tech-X Corporation.

GT1 68 Particle-In-Cell Simulation and Experimental Characterization of a Cylindrical Cusped Field Plasma Thruster* ANDREA LUCCA FABRIS, CHRISTOPHER YOUNG, *Stanford University* MARCO MANENTE, DANIELE PAVARIN, *University of Padova* MARK CAPPELLI, *Stanford University* This work aims to provide new insight into the physical mechanisms occurring in the discharge channel and acceleration region of a cusped field plasma thruster through a combined experimental and computational approach. Simulations are performed using the 3D particle-in-cell code F3MPIC, comprised of a PIC core coupled with a finite element electrostatic field solver over an unstructured mesh of tetrahedra. The cusped field structure is also included to resolve magnetized particle dynamics. We perform simulations with two ionization schemes: one where constant particle source rates are assigned to certain regions, and a more rigorous approach based on Monte Carlo collision events. The simulation results reveal correlations between the particle density distributions, electrostatic potential, and magnetic field topology inside the thruster discharge channel that are confirmed through experiments. Laser induced fluorescence measurements have resolved xenon ion velocities at several points near the thruster exit plane. Faraday and floating emissive probe measurements indicate this velocity field is correlated with the measured ion beam current profile and electrostatic potential field.

*This work sponsored by the U.S.A.F. Office of Scientific Research, with Dr. Mitat Birkan as program manager. F3MPIC developed under the European Union FP7 HPH.com project. C.V.Y. acknowledges the DOE NNSA SSGF fellowship under Contract DE-FC52-08NA28752.

GT1 69 Simulation of Neutral Particle Transport During HiPIMS* JAN TRIESCHMANN, SARA GALLIAN, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum* In this work the importance of the knowledge of the spatial distribution, its temporal evolution as well as their energy distribution of heavy particles within sputtering processes is discussed. To describe these discharges – typically operated at very low pressures below 1 Pa – specific modeling approaches are required. Our approach comprises a three-dimensional kinetic Lagrangian description of neutral particles. A modified version of the direct simulation Monte Carlo (DSMC) code *dsmcFoam* [1] is used, with the aim to describe the evolution of background and sputtered particles of a High Power Impulse Magnetron Sputtering (HiPIMS) process in a research reactor. Emphasize is put on the influence of the initial angular distribution of sputtered particles, as well as their energy distribution and its angular dependence. Based on the work of Stepanova and Dew [2] a modified Thompson energy distribution [3] is used. Differently distributed sputtered particles provide densities and fluxes concerning the corresponding film formation.

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

[1]T. J. Scanlon *et al.*, Comput. Fluids **39**, 2078 (2010).
[2]M. Stepanova and S. K. Dew, J. Vac. Sci. Technol. A **19**, 2805 (2001).
[3]M. W. Thompson, Phil. Mag. **18**, 377 (1968).

GT1 70 Numerical simulation of quantum systems using the Particle-In-Cell method* SVEN DIRKMANN, ZIAD YOUSSEF, TORBEN HEMKE, THOMAS MUSSENBROCK, *Ruhr University Bochum* The Particle-In-Cell (PIC) method is a very powerful method for studying the dynamics of plasmas. It has been primarily developed for tracking the charged particle trajectories subject to selfconsistent and external electromagnetic fields. Exploiting the power of modern computers, one is able to track the classical paths of tens of millions of particles at the same time. In the late 1980th, it was Dawson (and later Dauger) who had the idea to apply the PIC method to the classical part in the semiclassical approach to quantum systems via path integral methods. One could estimate that if a thousands of classical paths are sufficient to describe the dynamics of one quantum particle, then millions classical paths could describe the dynamics of a quantum particle system. A PIC code in the frame of a semiclassical approach would therefore enable the investigation of a number of quantum phenomena, e.g., optical properties, electrical properties, and, ultimately, chemical reactions. In this contribution we explain the use of the PIC code *yapic* (developed by the authors) in the frame of the path integral method and discuss the numerical results for simple quantum phenomena, i.e., the quantum harmonic oscillator and quantum tunneling.

*This work is supported by the German Research Foundation in the frame of FOR 2093.

TUESDAY EVENING \ GT1

GT1 71 Simulation of Saddle Coil and Helical Winding Magnetic Field Perturbation in the IR-T1 Tokamak YOUNES ADLTALAB, PEJMAN KHORSHID, ELHAM ABIZI MOGHADAM, *Department of Physics, College of Science, Mashhad Branch, Islamic Azad Univesity, Mashhad, Iran* The magnetic field of a set of saddle coils compared to the magnetic field of the helical winding coil on IR-T1 tokamak in a simulation method. The equation of helical windings that they mounted on vacuum chamber in a spiral modes (L = 2, n = 1) and (L = 3, n = 1), where L represents the number of toroidal rounds, and n represents the direction of the poloidal round, using Green function has been calculated, too. The coordinate system defined on a torus and an electric current applied to create a magnetic field and the magnetic field of resonant helical magnetic field disorders of the confinement were calculated in the whole space. In this study, the shape and structure of the Saddle coils has been defined toroidally and then poloidally configuration. The resulting simulation code is used to predict the position and structure of saddle coil that has same magnetic field generation with respect to Helical winding.

GT1 72 Space – time evolution of low-pressure H2 plasma induced by runaway photoelectrons produced by KrF laser pulse ALEXEY ZOTOVICH, ANDREY VOLYNETS, *Moscow State University, Department of Physics, Moscow, Russia* DMITRY LOPAEV, SERGEY ZYRYANOV, *Nuclear Physics Institute, Moscow State University, Moscow, Russia* DMITRY ASTAKHOV, VLADIMIR KRIVTSUN, KONSTANTIN KOSHELEV, *Institute of Spectroscopy RAS (ISAN), RD ISAN, Troitsk, Russia* Extreme Ultraviolet Lithography (EUVL) at 13.5 nm is expected to provide the next generation of ULSI. One of hot EUVL problems is contamination of EUV multilayer optics that compels to search methods of in-situ cleaning. The most promising method is to apply H2 plasma generated over the mirror surface by EUV radiation itself. Therefore investigations of EUV-induced plasma are of great interest for such cleaning technology developing. To model evolution of EUV-induced plasma, the study of H2 plasma induced by photoelectrons extracted from a surface by KrF laser pulse has been done. The experiment was carried out by the space-time resolved probe technique while the analysis was made with using plasma model based on 2D PIC MC code for both electrons and ions. Comparison of experimental and calculated evolution of probe characteristics provides correct applicability of the probe theory and allows one to reveal key mechanisms and parameters which control the evolution of photoelectrons-induced plasma.

GT1 73 Effect of cathode design on dc gas breakdown VALERIY LISOVSKIY,* RUSLAN OSMAYEV, VLADIMIR YEGORENKOV, *Kharkov National University, Svobody Sq.4, Kharkov 61022* This paper reports dc breakdown curves we registered between a flat anode and cathodes of various design (a flat one, two types of steps with different height, a cathode possessing a bump or an indentation at its center, cones of different height), the least inter-electrode distance was kept constant. We observed that the minima and the right-hand branches of breakdown curves coincided practically whereas the left-hand ones did not. At lower pressure a divergence of left-hand branches of breakdown curves was registered for cathodes of different design. For the step-wise cathodes near to or to the right of the breakdown curve minimum the gas breakdown occurs within the smallest gap between the upper part of the cathode and the flat anode. With the gas pressure lowering the breakdown occurs between the flat anode and the lateral surface of the step-wise cathode, and then its lower flat part. For conical cathodes the breakdown occurs either near its sharp edge or at the lateral surface of the cone at some distance from its edge.

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

GT1 74 Effect of inter-electrode gap on dc cathode sheath characteristics VALERIY LISOVSKIY,* EKATERINA ARTUSHENKO, VLADIMIR YEGORENKOV, *Kharkov National University, Svobody Sq.4, Kharkov 61022* We found in experiment that increasing the inter-electrode distance with the current fixed first leads to the growth of the voltage drop U across the cathode sheath as well as of its thickness d. This phenomenon is observed when the anode is located in the negative glow of the dc discharge. With longer distances when the anode is located in the dark Faraday space or positive column, the quantities U and d approach their saturation values and then remain unchanged. The current through the negative glow is supported by fast electrons generated in the cathode sheath where they also gained energy as well as by a diffusion flow. The anode departure from the cathode within the negative glow leads to a decrease of the fast electron flow, therefore a higher voltage U is required to support a fixed current what is accompanied by the cathode sheath thickness d growth. This phenomenon is clearly manifested in argon and nitrogen whereas it is expressed much weaker in electronegative gases (N_2O, O_2). An analytical model is proposed describing the phenomenon outlined.

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

GT1 75 Investigation of a cylindrical transparent cathode discharge MARK BOWDEN, TOM HARDIMENT, *University of Liverpool* The term Transparent Cathode Discharge (TCD) refers to a low-pressure electrical discharge also known as an Inertial Electrostatic Confinement (IEC) plasma. A defining characteristic is that the discharge is generated by a hollow, grid-constructed cathode and an outer, concentrically-arranged anode. Ions and electrons are accelerated by a large potential applied between the grids, with plasma being generated in different parts of the system depending on operating conditions. This project aims to study this device in order to assess its suitability for development as a reactive plasma source. A TCD device with concentric, cylindrical, mesh electrodes was operated in noble and molecular gases, and the discharge observed with a combination of emission imaging, emission spectroscopy and electrical probe diagnostic techniques. Preliminary measurements indicate that the alignment of the apertures in the inner and outer grid electrodes plays key role in determining discharge behaviour.

GT1 76 Second-harmonic generation in composite of microwave plasma and cm-order metamaterial AKINORI IWAI, YOSHIHIRO NAKAMURA, OSAMU SAKAI, *Kyoto University* Second-harmonic generation was observed by high-power microwave propagation in composite space of plasma and cm-order metamaterial. In principle, high-power electromagnetic waves induce nonlinear polarization and harmonic-wave generation in plasma, because plasma is nonlinear dielectric medium. However, plasma frequency dispersion prevents propagation of fundamental waves; the increase in electron density leads to the evolution of plasma frequency that behaves as a cut-off frequency, and plasma dielectric constant for fundamental waves becomes negative. To remove this difficulty, our setup combines plasma and double-split-ring resonator(DSRR) or another metamaterial, whose negative permeability has been verified theoretically and experimentally [1] in order to cancel out the cutoff property of negative permittivity using negative permeability: refractive index becomes a real and negative value. By enabling electromagnetic waves to propagate into high-density plasma, intense harmonic generation occurs. Our has reported unique properties of plasma metamaterial [2]. In this study, we experimentally observed second harmonic generation (at 4.9 GHz) in plasma space with DSRR at incident microwave frequency of 2.45 GHz.

[1]J. B. Pendry *et al.*, IEEE Trans. Microw. Theory Tech. **47**, 2075 (1999).
[2]O. Sakai *et al.*, Plasma Sources Sci. Technol. **21**, 013001 (2012).

GT1 77 Sustenance of electronegative plasma column in the presence of electron temperature gradient in linear magnetized plasma device SHANTANU KUMAR KARKARI, MIMANSA SHASTRI, HASMUKH KABARIYA, SANJAY MISHRA, *Institute for Plasma Research, Bhat Gandhinagar, Gujarat, India* NISHANT SIRSE, *Dublin City University, Ireland* Electronegative plasmas are widely popular in semiconductor processing industries as well as for the production of hydrogen neutral beams for plasma heating in fusion devices. This paper describes about the sustenance of electro-negative oxygen plasma in the presence of electron temperature gradient in magnetized plasma column of the linear plasma device. The electron temperature is self-consistently created in the discharge by the energy filtering of electrons across the magnetic field in conjunction with axial losses of energetic electrons at the grounded end plate. Detail measurements of radial plasma parameters performed using planar Langmuir probe finds substantial decrement in the negative to positive saturation current ratio as observed in the central region of the plasma column, characterized by low electron temperature. The negative ion fraction obtained from these measurements are based on a qualitative model that considers the modified Bohm speed in the presence of negative ions including the attenuation of thermal electron current to the probe due to the presence of external magnetic field.

GT1 78 Boundary Conditions and Heat Flux to the Walls in Two-Temperature L. PEKKER N. HUSSARY, *Victor Technologies, West Lebanon.*

SESSION HW1: NON-EQUILIBRIUM KINETICS AND BASIC PLASMA PHYSICS OF LOW TEMPERATURE PLASMAS

Wednesday Morning, 5 November 2014
Room: Ballroom EF at 8:00
Scott Walton, NRL, presiding

Contributed Papers

8:00

HW1 1 Modeling of electron beam-generated plasmas produced in Ar/N2 mixtures* TZVETELINA PETROVA, EVGENIA LOCK, GEORGE PETROV, DAVID BORIS, RICHARD FERNSLER, SCOTT WALTON, *Naval Research Lasboratory* We discuss a non-equilibrium collisional-radiative model coupled with electron kinetics developed to study the population dynamics in electron beam-generated plasmas produced in low pressure Ar/N_2 mixtures. Generally, these plasmas are characterized by low electron temperatures (1 eV), low plasma potentials, and plasma densities in the range 10^9-10^{11} cm^{-3}. We have shown both experimentally [1] and theoretically [2] that small admixtures of nitrogen to argon leads to changes in the electron energy distribution function (EEDF) resulting in a lowering of the electron temperature from 1.0 to 0.4 eV. The modeling results show that these changes strongly impact the production of argon excited states via changes in the collisional excitation rates. The contribution of different production and destruction mechanisms of 1s and 2p argon excited states is discussed in detail. The results of the modeling are compared with the experimentally measured EEDF, electron temperature, and the optical emission spectra in 700–850 nm range.

*Work supported by NRL Base 6.1. Program.

[1]D. R. Boris, G. M. Petrov, E. H. Lock, Tz. B. Petrova, R. F. Fernsler, and S. G. Walton, Plasma Sources Sci. Technol. **22**, 065004 (2013).
[2]G. M. Petrov, D. R. Boris, Tz. B. Petrova, E. H. Lock, R. F. Fernsler, and S. G. Walton, Plasma Sources Sci. Technol. **22**, 065005 (2013).

8:15

HW1 2 Ion instability in Tonks-Langmuir model with collisions T.E. SHERIDAN, *Ohio Northern University* The Tonks-Langmuir (TL) model describes a discharge with collisionless, kinetic ions and Boltzmann electrons. In the TL model, ions "born" throughout some volume are accelerated to the discharge walls by the self-consistent electric field in both the presheath and the sheath. That is, the TL model solves the Vlasov equation in a bounded geometry, and hence gives the full ion velocity distribution function. In this presentation, we consider the TL model in a one-dimensional planar geometry with a spatially-uniform source of warm ions. Ions are assumed to undergo "charge exchange" collisions with a constant collision frequency. We solve this model using a particle-in-cell (PIC) simulation. Preliminary investigations show that when the ion birth temperature is sufficiently low, and for collision frequencies which are a few percent of the ion plasma frequency, there is an ion instability in the presheath. At the same locations, the time-averaged ion distribution function displays three peaks, one of which may be associated with ions that inverse Landau damp on the waves.

8:30

HW1 3 Mechanism of N_2 Dissociation and Kinetics of N(^{4}S) Atoms in Pure Nitrogen Plasma* ANDREY VOLYNETS, *Lomonosov Moscow State University, Faculty of Physics* DMITRY LOPAEV, NIKOLAY POPOV, *Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics* This work deals with kinetics of the ground state nitrogen atoms N(^{4}S) and N_2 dissociation mechanism in pure N_2 plasma. The experiment was carried out in positive column of DC glow discharge for p = 5–50 Torr, J = 20–100 mA. N(^{4}S) balance was considered for spatially uniform conditions controlled by only two terms: source (characterized by effective production rate k_{eff}) and loss (characterized by effective loss time τ_{loss}). Analysis of k_{eff} and τ_{loss} gains considerably better understanding of N_2 dissociation. N/N_2 dissociation rate as function of discharge parameters was obtained using two independent optical methods: actinometry on Ar atoms and $N_2$2+ band emission decay at discharge modulation. With N/N_2 radial profiles N atom surface loss probability γ_N and then τ_{loss} were estimated. γ_N revealed to be dependent on N(^{4}S) concentration and thereby discharge conditions through the sorption balance of physisorbed N atoms. Phenomenological model taking into account basic surface processes provides γ_N data in good agreement with experiment. Finally, k_{eff} was obtained as function of E/N and it was shown that even EEDF calculated with accounting for N_2 vibrational excitation is unable to provide observed values of k_{eff}. Reasons of that fact are discussed in detail.

*The work was supported by RFBR (Grant #11-02-91063-CNRS) and by Optec Grant.

8:45

HW1 4 Modeling of vibrational kinetics in CO_2 dielectric barrier discharges S. PONDURI, *TU Eindhoven* M.M. BECKER, D. LOFFHAGEN, *INP Greifswald* S. WELZEL, M.C.M. VAN DE SANDEN, *DIFFER* R. ENGELN, *TU Eindhoven* CO_2 reduction to CO is considered to improve the prospects of CO_2 recycling which in turn could mitigate the greenhouse effect and serve as energy storage. Non equilibrium plasmas were used in the past to achieve high energy efficiencies in dissociating CO_2. Non equilibrium distribution in asymmetric stretch modes of CO_2, driven by vibrational up-pumping (VV process), has been suggested as key for achieving such high energy efficiencies. In this work, a time-dependent, one dimensional fluid model taking into account balance equations for the densities of all relevant species and electron mean energy is used to investigate the kinetics of VV process in a pure CO_2 dielectric barrier discharge. A Treanor like distribution has been observed in CO_2 asymmetric modes and the rates of dissociation have been obtained from these distributions. The rates thus obtained have proved to be significantly lower than the rates of other dissociating processes such as electron impact dissociation. The effect of power in-coupling, duration of plasma and pressure on the vibrational distributions and CO production rate is also studied.

9:00

HW1 5 ABSTRACT WITHDRAWN

9:15

HW1 6 Two-Stage Energy Thermalization Mechanism in Nanosecond Pulse Discharges in Air and Hydrogen-Air Mixtures IVAN SHKURENKOV, SUZANNE LANIER, IGOR ADAMOVICH, WALTER LEMPERT, *The Ohio State University* Time-resolved and spatially resolved rotational temperature measurements in air and H2-air, by purely rotational Coherent Anti-Stokes Raman Spectroscopy (CARS), are presented. The experimental results demonstrate high accuracy of pure rotational psec CARS for thermometry measurements at low partial pressures of oxygen in nonequilibrium plasmas. The results are compared with modeling calculations using a state-specific master equation kinetic model of reacting hydrogen-air plasmas, showing good agreement. The results demonstrate that energy thermalization and temperature rise in these plasmas occur in two stages, (i) "rapid" heating, occurring on the time scale $\tau_{rapid} \sim 0.1$–$1\ \mu s \cdot atm$, caused by collisional quenching of excited electronic states of N_2 molecules by O_2, and (ii) "slow" heating, on the time scale $\tau_{slow} \sim 10$–$100\ \mu s \cdot atm$, caused primarily by N_2 vibrational relaxation by O atoms (in air) and by chemical energy release during partial oxidation of hydrogen (in H_2-air. Both energy thermalization mechanisms have major implications for plasma assisted combustion and plasma flow control.

SESSION HW2: DUSTY PLASMAS AND NEGATIVE IONS

Wednesday Morning, 5 November 2014
Room: State C at 8:00
Masaru Shiratani, Kyushu University, presiding

Contributed Papers

8:00

HW2 1 Coulomb Crystals in Cylindrical Dusty Plasmas under Gravity/Microgravity* KAZUO TAKAHASHI, *Department of Electronics, Kyoto Institute of Technology* HIROO TOTSUJI, SATOSHI ADACHI, *Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency* Coulomb crystals of dusty plasmas have been studied under microgravity with utilities boarding on the International Space Station in a joint Russian/German research project. Dynamics of the Coulomb crystals in cylindrical plasmas is investigated with the apparatus of PK-4 being launched till the end of 2014. A science team in Japan studied the cylindrical dusty plasmas to contribute to the project with the PK-4J modified original for microgravity experiments of parabolic flights in Japan. In the experiments, the dust particles distributed at the off-centered position close to the bottom in balancing of gravity. Under microgravity, they changed the distribution and formed a Coulomb crystal around the center axis in the plasmas. Several particles arranged in a line parallel to the axis, and the lines piled up to a bundle [1]. Spatial distribution of the dust particles affects on plasma parameters of ion density and electron temperature. Structures of the Coulomb crystals connected to the parameters are discussed.

*The present study were supported by JAXA and Diamond Air Service.

[1]K. Takahashi, M. Tonouchi, S. Adachi, and H. Totsuji, Int. J. Microgravity Sci. Appl. **31**, 62 (2014).

8:15

HW2 2 Langmuir probe measurements of the electron energy probability function and laser scattering in nanodusty plasmas* NARULA BILIK, YUNXIANG QIN, *University of Minnesota - Mechanical Engineering* ERAY AYDIL, *University of Minnesota - Chemical Engineering and Materials Science* UWE KORTSHAGEN, *University of Minnesota - Mechanical Engineering* A Langmuir probe was used to measure real-time electron energy probability distribution function (EEPF) in argon-silane dusty plasma generated by a RF capacitive reactor. The challenge of Langmuir probe measurements in dusty plasma is the coating of the probe surface: A dielectric layer formed by dust particles causes a series resistance and changes the probe work function, leading to inaccuracy in EEPF measurements. We addressed this problem by adding an actuated ceramic shield to the probe. With the actuated shield the probe was exposed to the dusty plasma only when it was measuring and under rapid I-V scan, minimizing the exposure and effectively preventing coating. EEPFs in dusty plasma were captured in 80mtorr and 40 W dusty plasma (10 sccm argon and 4.7 sccm 5% silane in argon flow). Simultaneous measurements of the ion density with a capacitive probe and real-time laser scattering was performed to further characterize the plasma. As particles form in dusty plasma, the electron density dropped but electron temperature increased. The electron density in the dusty plasma dropped much more compared to the ion density due to the attachment of electrons to the growing particles.

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

8:30

HW2 3 Correlation between nanoparticles formation and plasma parameters evolution in magnetically confined C_2H_2/Ar plasma GEORGES AL MAKDESSI, JOELLE MARGOT, *University of Montreal* RICHARD CLERGEREAUX, *University of Paul Sabatier* Dusty plasmas are plasmas containing charged nano-sized or even charged micro-sized particles. Known for decades, dusty plasmas have attracted the interest of the scientific community in the early 80s, especially in astrophysics when dusty particles were discovered in the rings of Saturn [1]. Comets and planetary rings are some examples of natural objects formed by dusty plasmas [2]. Dusty particles are also found in laboratories plasmas such as those used for deposition and etching of thin films. In this presentation, we investigate magnetically confined low pressure dusty plasmas in acetylene. The plasma is created by an electromagnetic surface wave at a frequency of 200 MHz. By performing a parametric study of the influence of the magnetic field on the formation of dust particles and on the plasma properties, we expect to achieve a good understanding of their creation mechanisms, and, ultimately to control their characteristics.

[1]B. A. Smith *et al.*, Science **215**, 504 (1982).
[2]C. K. Goeretz, Rev. Geophys. **27**, 271 (1989).

8:45

HW2 4 Nanoparticle heating at atmospheric pressures* NICOLAAS KRAMER, *University of Minnesota - Mechanical Engineering* ERAY AYDIL, UWE KORTSHAGEN, *University of Minnesota - Chemical Engineering and Materials Science* Plasma growth and crystallization of nanoparticles is an exciting new frontier both for plasma science as well as materials research. To date, the mechanisms of nanoparticle charging and heating in nonthermal plasmas have been studied and understood to some extent for low pressure plasmas. However, particle charging and heating at atmospheric pressures have been little explored. The fundamental processes of nanoparticle charging and heating are significantly different at atmospheric pressure compared to low pressures. Charging is determined through collision enhanced or hydrodynamic, mobility driven collection of ions by the nanoparticles rather than by orbital motion at low pressures. Nanoparticle heating reactions have to compete with nanoparticle cooling through convection/conduction to the neutral gas that is about 100–1000 times faster than at low pressure. Here, we present a Monte Carlo model that stochastically treats nanoparticle heating reactions such as electron-ion recombination and energetic surface reactions. Nanoparticle cooling through conduction/convection is modeled through a continuum model. The model indicates at atmospheric pressure, the nanoparticle temperature on average remains much closer to the gas temperature than at low pressure.

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

[2]P. Agarwal and S. L. Girshick, Plasma Chem. Plasma Process **34**, 489 (2014).

9:00

HW2 5 Numerical Modeling of a Pulsed Argon-Silane RF Plasma with Biased Substrate for High-Velocity Deposition of Nanoparticles* STEVEN GIRSHICK, CARLOS LARRIBA-ANDALUZ, *Dept. of Mechanical Engineering, University of Minnesota, Minneapolis, MN* It has been hypothesized that deposition of very small silicon nanoparticles during plasma-enhanced chemical vapor deposition of silicon, under conditions where the particle impact velocity is high enough to cause particle melting/amorphization, can lead to epitaxial film growth at low temperature [1]. One way to accomplish this might be by pulsing the RF plasma and applying a positive DC bias during the afterglow of each pulse. The negatively charged particles, trapped in the plasma during the ON phase of each pulse, are accelerated to the substrate during the afterglow. To assess the feasibility of such an approach, we conducted numerical simulations of a pulsed capacitively-coupled RF Ar-silane plasma. We used a modified version of a previously reported 1D model, in which a nanodusty plasma is simulated by self-consistently coupling models for the plasma, chemistry and aerosol [2]. Preliminary results indicate that the approach is feasible, but that parameters such as pulse frequency and duty cycle are important in limiting particle growth and in maximizing fluxes of energetic nanoparticles to the substrate.

*Partially supported by US Dept. of Energy Office of Fusion Energy Science (DE-SC0001939) and US National Science Foundation (CHE-124752).

[1]P. Roca i Cabarrocas, R. Cariou, and M. Labrune, J. Non-Cryst. Sol. **358**, 2000 (2012).

9:15

HW2 6 Hydrogen negative-ion surface production on diamond materials in low-pressure H2 plasmas* GILLES CARTRY, KOSTIANTYN ACHKASOV, CÉDRIC PARDANAUD, JEAN-MARC LAYET, *PIIM, Aix Marseille University, CNRS* ALAIN SIMONIN, *IRFM, CEA Cadarache* ALIX GICQUEL, *LSPM, CNRS, Paris Nord University* PIIM COLLABORATION, IRFM COLLABORATION, LSPM COLLABORATION Negative-ion sources producing H-current density of ~200 A/m2 are required for the heating of the fusion plasma of the international project ITER. The only up-to-date solution to reach such a high H-negative-ion current is the use of cesium (Cs). Deposition of Cs on the negative-ion source walls lowers the material work function and allows for high electron-capture efficiency by incident particles and thus, high negative ion yields. However, severe drawbacks to the use of Cs have been identified and its elimination from the fusion negative-ion sources would be highly valuable. Volume production is not efficient enough at low-pressure to reach the high current required. Therefore, we are working on alternative solutions to produce high yield of H-negative-ions on surfaces in Cs-free H2 plasmas. In this communication, we will detail the methodology employed to study negative-ion surface production. In particular we will describe how the negative-ions are extracted from the plasma, and how we can obtain information on surface production mechanisms from the measurement of the H-energy distribution functions. We will present some results obtained on diamond surfaces and show that diamond is a promising candidate as a negative-ion enhancer material in low-pressure H2 plasmas.

*EFDA, FR-FCM, ANR, PACA are acknowledged for their support.

SESSION HW3: PLASMA INTERACTIONS WITH BIOLOGICAL SURFACES

Wednesday Morning, 5 November 2014; Room: State D at 8:00; Masafumi Ito, Meijo University, presiding

Invited Papers

8:00

HW3 1 Cold flame on Biofilm - Transport of Plasma Chemistry from Gas to Liquid Phase

MICHAEL KONG, *Old Dominion University*

One of the most active and fastest growing fields in low-temperature plasma science today is biological effects of gas plasmas and their translation in many challenges of societal importance such as healthcare, environment, agriculture, and nanoscale fabrication and synthesis. Using medicine as an example, there are already three FDA-approved plasma-based surgical procedures for tissue ablation and blood coagulation and at least five phase-II clinical trials on plasma-assisted wound healing therapies. A key driver for realizing the immense application potential of near room-temperature ambient pressure gas plasmas, commonly known as cold atmospheric plasmas or CAP, is to build a sizeable interdisciplinary knowledge base with which to unravel, optimize, and indeed design how reactive plasma species interact with cells and their key components such as protein and DNA. Whilst a logical objective, it is a formidable challenge not least since existing knowledge of gas discharges is largely in the gas-phase and therefore not directly applicable to cell-containing matters that are covered by or embedded in liquid (e.g. biofluid). Here, we study plasma inactivation of biofilms, a jelly-like structure that bacteria use to protect themselves and a major source of antimicrobial resistance. As 60–90% of biofilm is made of water, we develop a holistic model incorporating physics and chemistry in the upstream CAP-generating region, a plasma-exit region as a buffer for as-phase transport, and a downstream liquid region bordering the gas buffer region. A special model is developed to account for rapid chemical reactions accompanied the transport of gas-phase plasma species through the gas-liquid interface and for liquid-phase chemical reactions. Numerical simulation is used to illustrate how key reactive oxygen species (ROS) are transported into the liquid, and this is supported with experimental data of both biofilm inactivation using plasmas and electron spin spectroscopy (ESR) measurement of liquid-phase ROS.

Contributed Papers

8:30

HW3 2 Evaluation of the Efficacy of the Plasma Pencil Against Cancer Cells SOHEILA MOHADES, NAZIR BAREKZI, HAMID RAZAVI, MOUNIR LAROUSSI, *Old Dominion University* The plasma pencil generates low temperature and atmospheric pressure plasma. To generate the plasma, high voltage pulses with short width (from nanosecond to microsecond) are applied to a noble gas. The working gas can be helium, argon or a mixture of these with air or oxygen. Generating plasma with helium provides a tolerable temperature for biological cells and tissues. Diagnostic measurements on the plasma plume has revealed the presence of active agents such as reactive oxygen species (ROS) and nitrogen reactive species (RNS), which are known to have biological implications. Recently, low temperature plasma has drawn attention to its potential in cancer therapy. In our lab, the plasma pencil has been used to treat leukemia, prostate and epithelial cancer cells [1]. The cancer cell line used here is the SCaBER (ATCC®HTB3™) cell line originating from a human bladder cancer. The results indicate that specific species induce the molecular mechanisms associated with cell death. The death of cells after plasma treatment will be studied using assays, such as DNA laddering and Caspase-3 activation, to elucidate the mechanism of the apoptotic or necrotic pathways.

[1]N. Barekzi and M. Laroussi, Plasma Process. Polym. **10**, 1039 (2013).

8:45

HW3 3 Multiple Pulses from Plasma Jets onto Liquid Covered Tissue* SETH NORBERG, WEI TIAN, ERIC JOHNSEN, MARK J. KUSHNER, *University of Michigan* Atmospheric pressure plasma jets are being studied in the treatment of biological surfaces that are often covered by a thin layer of liquid. The plume of the plasma jet contains neutral radicals and charged species that solvate into the liquid and eventually form terminal species that reach the tissue below. The contribution of neutral and charged species to reactivity in the liquid is sensitive to whether the active plasma plume touches the liquid. In this paper, we discuss results from modeling the production of the aqueous species formed from the interaction of the plume of plasma jets over multiple pulses with the water layer, and the fluences of the species to the underlying tissue. The model used in this study, *nonPDPSIM*, solves transport equations for charged and neutral species and electron energy, Poisson's equation for the electric potential, and Navier-Stokes equations for the neutral gas flow. Radiation transport includes photoionization of O_2 and H_2O in the gas and liquid phases and photodissocation of H_2O_{aq} in the liquid. Multiple pulses when the plasma plume touches and does not touch the liquid will be examined. Two regimes of hydrodynamics will be discussed – low repetition rates where the neutral radicals are blown away before the next discharge pulse, and high repetition rate when the plasma plume interacts with neutral radicals from previous pulses. The density of aqueous ions produced in the liquid layer is strongly dependent on whether the plasma effluent touches or does not touch the water surface.

*Work supported by DOE Office of Fusion Energy Science and NSF.

9:00

HW3 4 Atomic oxygen characteristics in a dielectric barrier discharge developed for wound treatment* SABRINA BALDUS, *Institute for Plasma Technology, Ruhr University Bochum* DANIEL SCHROEDER, VOLKER SCHULZ-VON DER GATHEN, *Institute for Experimental Physics II, Ruhr University Bochum* NIKITA BIBINOV, PETER AWAKOWICZ, *Institute for Plasma Technology, Ruhr University Bochum* Nowadays, infected chronic wounds are a major problem of society. Atmospheric pressure plasmas like dielectric barrier discharges (DBDs) have already shown their ability of improving the wound healing process of chronic wounds in clinical trials. Yet, the mechanism of action is poorly understood. A DBD comprising a single driven electrode is a beneficial configuration for wound treatment. The patient itself functions as the counter electrode. Hence, reactive oxygen species (ROS) like ozone or atomic oxygen produced in the plasma reach the wound directly. Some ROS, including superoxide or nitric oxide, are produced by skin cells to repulse invading bacteria. Nevertheless, a very high amount of ROS leads to oxidative stress and can cause cell damage or even cell death. Therefore it is crucial to have a well characterized plasma for effective wound treatment. Plasma parameters are determined using absolutely calibrated optical emission spectroscopy. Density of atomic oxygen is measured applying xenon-calibrated two photon absorption laser induced fluorescence spectroscopy. A simulation of the afterglow chemistry, developed to gain insight in the characteristics of the atomic oxygen and its flux towards the treated surface, is cross-checked with measurement results.

*Work supported by the German Research Foundation within PAK816.

9:15

HW3 5 Long Term Effects of Multiple DBD Pulses on Thin Liquid Layers Over Tissue: Reactive Fluences and Electric Fields* WEI TIAN, MARK J. KUSHNER, *University of Michigan* Atmospheric dielectric barrier discharges (DBDs) are used in treatment of tissue, often covered by thin liquid layers. The reactivity reaching the tissue depends on the plasma dose, composition and acidification of the liquid, and the cumulative delivery of electric fields through the liquid. In this paper, we report on a computational investigation of the interaction of DBDs with a thin liquid layer covering tissue over many minutes. We used *nonPDPSIM*, a 2-d model in which Poisson's equation, the electron temperature equation, transport equations for charged and neutral species and radiation transport are solved in both the gas and liquid. The liquid layer, 100's μm thick, is water with dissolved gases [O_{2aq} (aq is aqueous), CO_{2aq}], metal ions (Fe^{2+}_{aq}, Fe^{3+}_{aq}), and organics (RH_{aq}). Hundreds of pulses at 100 Hz are computed, followed by minutes of afterglow. In the liquid, transient radicals (OH_{aq}, H_{aq}) are produced during the discharge pulse and are consumed during the interpulse period. Terminal species (H_2O_{2aq}, O_{3aq}) accumulate and diffuse to the tissue. Ions are dominated by $NO_3{-}_{aq}$, $O_2{-}_{aq}$ and $H_3O^+_{aq}$. Production of HNO_{3aq} and $HOONO_{aq}$ is assisted by O_{2aq} for the first pulses and then O_{3aq}. Accumulating nitric acid lowers the pH. RH_{aq} consumes most reactive oxygen species in the early plasma treatment leaving R_{aq}. With longer exposure, RH_{aq} can be consumed, enabling more ROS to reach the tissue. The cumulative exposure of electric fields to the tissue depends on the increasing conductivity of the liquid.

*Work supported by DOE Office of Fusion Energy Science and NSF.

SESSION JW1: THE WILL ALLIS PRIZE FOR THE STUDY OF IONIZED GASES
Wednesday Morning, 5 November 2014; Room: State EF at 10:00; Mark Kushner, University of Michigan, presiding

Invited Papers

10:00
JW1 1 Future Low Temperature Plasma Science and Technology: Attacking Major Societal Problems by Building on a Tradition of Scientific Rigor*
DAVID GRAVES, *University of California at Berkeley*

Low temperature plasma (LTP) science is unequivocally one of the most prolific areas for varied applications in modern technology. For example, plasma etching technology is essential for reliably and rapidly patterning nanometer scale features over areas approaching one square meter with relatively inexpensive equipment. This technology enabled the telecommunication and information processing revolution that has transformed human society. I explore two concepts in this talk. The first is that the firm scientific understanding of LTP is and has been the enabling feature of these established technological applications. And the second is that LTP technology is poised to contribute to several emerging societal challenges. Beyond the important, ongoing applications of LTP science to problems of materials processing related to energy generation (e.g. thin film solar cell manufacture), there are novel and less well known potential applications in food and agriculture, infection control and medicine. In some cases, the potentially low cost nature of the applications in so compelling that they can be thought of as examples of frugal innovation.

*Supported in part by NSF and DoE.

SESSION JW2: GEC BUSINESS MEETING
Wednesday Morning, 5 November 2014
Room: State AB at 11:00
Amy Wendt, University of Wisconsin, presiding

Contributed Papers

11:00
JW2 1 GEC Business Meeting

SESSION KW1: PLASMA DIAGNOSTICS II
Wednesday Afternoon, 5 November 2014; Room: State EF at 13:30; Hiroshi Akatsuka, Tokyo Institute of Technology, presiding

Invited Papers

13:30
KW1 1 Diagnostics of plasma-surface interactions in plasma processes
KENJI ISHIKAWA, *Nagoya University*

Low temperature plasma including electrons, ions, radicals and photons can be applied because only high temperature of electron but for background gases. Recently plasma applications in biology and medicine have grown significantly. For complexity of mechanisms, it is needed to understand comprehensively the plasma-surface interactions. To diagnose the interactions comprises of three areas; (1) incident species generated in plasmas toward the surface, (2) surface reactions such as scission and bond of chemical bonds, and (3) products after the reactions. Considered with non-linearity of the chemical reactions as changed by an initial state, we have focused and developed to observe dangling bonds in situ at real time by electron spin resonance (ESR). Moreover, individual contribution and simultaneous irradiation of each species such as radicals and photons have been studied in utilization of light shades and windows in similar manner of the pellets for plasma process evaluation (PAPE) [1]. As exampled, the interaction of polymeric materials [2], fungal spores [3] and edible meats with plasmas were studied on the basis of the real time in situ observations of dangling bonds or surface radicals formation.

[1]S. Uchida *et al.*, J. Appl. Phys. **103**, 073303 (2008).
[2]K. Ishikawa *et al.*, J. Phys. Chem. Lett. **2**, 1278 (2011).
[3]K. Ishikawa *et al.*, Appl. Phys. Lett. **101**, 013704 (2012).

Contributed Papers

14:00
KW1 2 Phase-modulated dispersion interferometry for electron-density determination of high-pressure plasma*
KEIICHIRO URABE, *The University of Tokyo* TSUYOSHI AKIYAMA, *National Institute for Fusion Science* KAZUO TERASHIMA, *The University of Tokyo* Phase-modulated dispersion interferometry (PMDI) is a laser interferometry technique that was first developed for measurement of electron density in large fusion reactors [1]. PMDI can eliminate the effect of nondispersive components in the refractive-index variation on the measured

signals; therefore, it is mostly free from vibration of optical devices during the measurement. Also, configuration of the laser beam axis in PMDI is simpler than that in heterodyne interferometry. In this paper, we demonstrate the potential of PMDI for the diagnostics of low-temperature plasmas generated at high pressures. Most of the variation of the refractive index induced by the variation of gas density was eliminated by signal processing, and it contributed to accurate electron-density determination in high-pressure plasmas [2]. The measurement results for a pulsed-dc microdischarge in an atmospheric-pressure helium gas flow revealed that the electron density in the microdischarge was in the range between 4×10^{13} and 1.4×10^{14} cm^{-3}, and our PMDI system had a temporal resolution of 110 μs and a sensitivity of the line-integrated electron density of 7×10^{11} cm^{-2} respectively.

*This work is supported in part by MEXT of Japan, JSPS, and NIFS.

[1]T. Akiyama *et al.*, Plasma Fusion Res. **5**, S1041 (2010).
[2]K. Urabe *et al.*, J. Phys. D **47**, 262001 (2014).

14:15
KW1 3 In-situ diagnostics and characterization of etch byproduct deposition on chamber walls during halogen etching of silicon NEEMA RASTGAR, SARAVANAPRIYAN SRIRAMAN, RICKY MARSH, ALEX PATERSON, *Lam Research* Plasma etching is a critical technology for nanoelectronics fabrication, but the use of a vacuum chamber limits the number of in-situ, real-time diagnostics measurements that can be performed during an etch process. Byproduct deposition on chamber walls during etching can affect the run-to-run performance of an etch process if there is build-up or change of wall characteristics with time. Knowledge of chamber wall evolution and the composition of wall-deposited films are critical to understanding the performance of plasma etch processes, and an in-situ diagnostics measurement is useful for monitoring the chamber walls in real time. We report the use of attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) to perform in-situ diagnostics of a vacuum chamber's walls during plasma etching. Using ATR-FTIR, we are able to monitor the relative thickness and makeup of chamber wall deposits in real time. We then use this information to develop a chamber wall cleaning process in order to maintain reproducible etching conditions from wafer to wafer. In particular, we report mid-IR (4000-650 cm^{-1}) absorption spectra of chamber wall-deposited silicon byproducts formed during halogen etching of silicon wafers.

14:30
KW1 4 Accurate characterization of RF antennas for low-temperature plasma discharges with non-uniform magneto-static fields DAVIDE MELAZZI, *University of Padova, Padova, Italy* VITO LANCELLOTTI, *Eindhoven University of Technology, Eindhoven, The Netherlands* ALESSANDRO CARDINALI, *ENEA Unità Tecnica Fusione, Rome, Italy* MARCO MANENTE, *T4i S.r.l., Padova, Italy* DANIELE PAVARIN, *University of Padova, Padova, Italy* The analysis of Radio Frequency Helicon plasma sources appears to have focused on the absorption of electromagnetic energy, but not much on the role played by the antenna driving the plasma discharge. In fact, most approaches assume (i) the induced current density on the antenna a priori, and (ii) a uniform magneto-static field aligned with the plasma column. To determine the antenna current self-consistently and to consider non-uniform magneto-static fields we have developed two codes: ADAMANT and RAYWh. The former implements a full-wave approach to evaluate the current distribution on the antenna and the antenna impedance, which is crucial for the design of the feeding network. RAYWh solves the 3D Maxwell-Vlasov model equations by a WKB asymptotic expansion, and is capable of predicting the occurrence of mode transitions. We report on a comparative study of various antennas working in the 1–30 MHz range commonly used in Helicon sources. The current distribution on the antenna, power deposition, and wave propagation phenomena have been investigated for various density profiles, magneto-static field configurations, neutral pressure, electron temperature.

14:45
KW1 5 Electron Density Measurement of Argon Containing Plasmas by Saturation Spectroscopy* S. NISHIYAMA, H. WANG, S. TOMIOKA, K. SASAKI, *Hokkaido University* Langmuir probes are widely used for electron density measurements in plasmas. However, the use of a conventional probe should be avoided in a plasma which needs high purity because of the possibility of contamination. Optical measurements are suitable for these plasmas. In this work, we applied saturation spectroscopy to the electron density measurement. The peak height of the saturation spectrum is affected by the relaxation frequency of the related energy levels. In the case of the metastable levels of argon, the electron impact quenching rate, which is proportional to the electron density, is the dominant factor. In our experiments, an inductively coupled plasma source and a tunable cw diode laser were used. The frequency of the laser was scanned over the Doppler width of the $4s[3/2]_2^o - 4p[3/2]_2$ (763.51 nm) transition. The experimental saturation spectrum was composed of a sharp Lorentzian peak and a broad base component, which was caused by velocity changing collisions. We deduced a new relationship between the saturation parameter and the measured saturated absorption spectrum with considering velocity changing collisions. We confirmed a linear relationship, which was expected theoretically, between the inverse of the saturation parameter and the electron density.

*Part of this work is supported by JSPS KAKENHI Grant Number 24540529.

15:00
KW1 6 OH(A,X) radicals in microwave plasma-assisted combustion of methane/air* WEI WU, CHE FUH, CHUJI WANG, *Mississippi State University* LASER SPECTROSCOPY AND PLASMA TEAM A novel microwave plasma-assisted combustion (PAC) system, which consists of a microwave plasma-assisted combustor, a gas flow control manifold, and a set of optical diagnostic systems, was developed as a new test platform to study plasma enhancement of combustion. Using this system, we studied the state-resolved OH(A,X) radicals in the plasma-assisted combustion and ignition of a methane/air mixture. Experimental results identified three reaction zones in the plasma-assisted combustor: the plasma zone, the hybrid plasma-flame zone, and the flame zone. The OH(A) radicals in the three distinct zones were characterized using optical emission spectroscopy (OES). Results showed a surge of OH(A) radicals in the hybrid zone compared to the plasma zone and the flame zone. The OH(X) radicals in the flame zone were measured using cavity ringdown spectroscopy (CRDS), and the absolute number density distribution of OH(X) was quantified in two-dimension. The effect of microwave argon plasma on combustion was studied with two different fuel/oxidizer injection patterns, namely the premixed methane/air injection and the nonpremixed (separate) methane/air injection. Parameters investigated included the flame geometry, the lean flammability limit, the emission spectra, and rotational temperature. State-resolved OH(A,X) radicals in the PAC of both injection patterns were also compared.

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

15:15

KW1 7 Ion Flux and Energy Virtual Sensor for Measuring Ion Flux and Energy Distribution at a RF Biased Electrode in ICP Reactor (RIE-MODE)* MARIA BOGDANOVA, *1 Skobeltsyn Insitute of Nuclear Physics, Moscow State University, SINP MSU, Moscow Russia; 2 Faculty of Physics, Moscow State University, MSU, Moscow* DMITRIY LOPAEV, *Skobeltsyn Insitute of Nuclear Physics, Moscow State University, SINP MSU, Moscow Russia* SERGEY ZYRYANOV, *1 Skobeltsyn Insitute of Nuclear Physics, Moscow State University, SINP MSU, Moscow Russia; 2 Faculty of Physics, Moscow State University, MSU, Moscow* The modern technology of micro- and nanoelectronics involves a great number of steps, e.g. pattern transfer, where Reactive Ion Etching (RIE) in rf plasma reactors is widely used. RIE is carried out placing samples on the surface of rf biased electrode, as rule in an asymmetric rf low-pressure discharge. In an effort to control the etching process, ion flux and energy distribution should be controlled precisely as much as possible. However, measurements of them during the process in the real-time operation mode are impossible. Nevertheless, if virtual sensor of ion flux and energy can be developed, such a sensor would allow monitoring ion energy spectrum without direct measurements during plasma processing. This virtual plasma diagnostics should include calculation of ion energy spectrum based on the simple physical model of ion motion in collisionless rf sheath. In addition the modeling has to be fulfilled in the real-time operation mode by using the set of external measurable parameters. This paper is just devoted to creation of such ion energy distribution virtual diagnostics.

*The reported study was supported by RFBR, research Project No. 14-02-31599.

SESSION KW2: REACTIVE MICRODISCHARGES
Wednesday Afternoon, 5 November 2014
Room: State C at 13:30
David Go, University of Notre Dame, presiding

Contributed Papers

13:30

KW2 1 Influence of the amount of N_2 admixture on the dynamics of atmospheric pressure helium discharges in capillary tubes ANNE BOURDON, FRANCOIS PECHEREAU, PEDRO VIEGAS, *EM2C laboratory, Ecole Centrale Paris* Since a few years, atmospheric pressure helium microplasma jets ignited in thin dielectric tubes have received considerable interest due to their potential for biomedical applications. In particular, the propagation of discharges in long capillary tubes is studied for the development of medical devices for endoscopic applications. In [1], experiments have been carried out to study the influence of various amounts of N_2 admixture on the characteristics of a helium discharge in long capillary tubes. In this work, we study with a 2D fluid model the discharge characteristics in conditions close to those used in experiments. Simulation results show that the discharge dynamics and structure depend on the amount of N_2 admixture and the applied voltage. In particular, as the amount of N_2 admixture increases, the propagation velocity of the discharge in the tube first increases and then decreases, as observed in experiments. To explain these results, a detailed analysis of the kinetic scheme of He-N_2 mixtures with various amounts of N_2 is presented. The influence of other parameters as the initial preionization level, the tube material and the shape of the applied voltage are also discussed.

[1]T. Darny, E. Robert, S. Dozias, and J. M. Pouvesle, Proceedings of GD (2014).

13:45

KW2 2 Production of Energetic Active-Oxygen Species at Atmospheric Pressure by Linear Microplasma Arrays* WILSON RAWLINS, KRISTIN GALBALLY-KINNEY, STEVEN DAVIS, *Physical Sciences Inc., Andover MA* ALAN HOSKINSON, JEFFREY HOPWOOD, *Electrical and Computer Engineering Department, Tufts University, Medford MA* Linear arrays of stripline resonators operated at microwave frequencies and low powers provide spatially and temporally continuous micro-discharges with high E/N at atmospheric pressure. When implemented in a discharge-flow reactor, these microplasmas excite metastable singlet molecular oxygen and dissociate oxygen molecules to produce atomic oxygen, with efficiencies comparable to conventional microwave resonant cavities at low pressures. At elevated pressure, production of atomic oxygen leads to prompt formation of ozone immediately downstream of the discharge exit. We have observed and quantified the production of $O_2(a\,^1\Delta)$ metastables and O_3 in the effluent of linear microplasma arrays for O_2/He, O_2/Ar, O_2/N_2/He, and O_2/N_2/Ar mixtures as functions of pressure, gas flow rate, and species mixing ratio. We compare results for single-array microplasmas, where the discharge products are formed in a small volume and entrained into the bulk flow, and overlapping dual-array microplasmas which process larger gas flow volumes.

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

14:00

KW2 3 High Frequency Self-pulsing Microplasmas* JOHN LASSALLE, WILLIAM POLLARD, DAVID STAACK, *Texas A&M University* Pulsing behavior in high-pressure microplasmas was studied. Microplasmas are of interest because of potential application in plasma switches for robust electronics. These devices require fast switching. Self-pulsing microplasmas were generated in a variable-length spark gap at pressures between 0 and 220 psig in Air, Ar, N_2, H_2, and He for spark gap lengths from 15 to 1810 μm. Resulting breakdown voltages varied between 90 and 1500 V. Voltage measurements show pulse frequencies as high as 8.9 MHz in argon at 100 psig. These findings demonstrate the potential for fast switching of plasma switches that incorporate high-pressure microplasmas.

*Work was supported by the National Science Foundation, Grant #1057175, and the Department of Defense, ARO Grant #W911NF1210007.

14:15

KW2 4 Conversion of carbon dioxide to carbon monoxide using non-thermal radio-frequency microplasmas at atmospheric pressure* JAMES DEDRICK, *York Plasma Institute, University of York* JAMES COMERFORD, *Green Chemistry Centre of Excellence, University of York* ZAENAB ABD-ALLAH, *Now at the University of Liverpool* KARI NIEMI, DEBORAH O'CONNELL, *York Plasma Institute, University of York* MICHAEL NORTH, *Green Chemistry Centre of Excellence, University of York* TIMO GANS, *York Plasma Institute, University of York* The conversion of carbon dioxide to carbon monoxide using non-thermal plasmas offers the potential to provide a sustainable and efficient source of carbon monoxide that is widely used in industry. To maximise conversion efficiency, a non-thermal microplasma source is developed to operate at 40.68 MHz in helium while minimising the potential for arcing. Operation in argon is also achieved and this offers the possibility for the future upscaling of production. Measurements of the concentration of carbon monoxide in the effluent are undertaken using Fourier transform infrared spectroscopy and combined with electrical measurements to estimate the efficiency of conversion with respect to variations in the applied voltage and inlet gas composition. The production of carbon monoxide concentrations greater than 1000 ppm (using a 1% carbon dioxide admixture in helium) facilitates the use of this method for simple chemical reactions including the generation of carbonyl functionalised molecules.

*JD acknowledges the support of an Endeavour Research Fellowship from the Australian Government.

14:30

KW2 5 Air-Plasma Bullets Propagating Inside Microcapillaries and in Ambient Air DEANNA A. LACOSTE, ANNE BOURDON, *CNRS UPR288 Laboratoire EM2C, Ecole Centrale Paris* KOICHI KURIBARA, KEIICHIRO URABE, SVEN STAUSS, KAZUO TERASHIMA, *Department of Advanced Materials Science, Graduate School of Frontier Sciences, The University of Tokyo* We report on the characterization of air-plasma bullets formed inside microcapillary tubes and in ambient air, obtained without the use of inert or noble gases. The bullets are produced by nanosecond discharges, applied at 1 kHz in a dielectric barrier discharge configuration. The anode consists of a tungsten wire with a 50-μm diameter, centered in the microcapillary, while the cathode is a silver ring, fixed on the outer surface of the fused silica tube. The gap distance is kept constant at 1.35 mm. The microcapillary is fed with a 4-sccm flow of air at atmospheric pressure. In the tubes and in ambient air, the propagation of air plasma bullets is observed. The temporal evolution of the bullet propagation has been studied with the aid of an ICCD camera. The effect of the applied voltage (from 5.2 to 8.2 kV) and the inner diameter of the microcapillaries (from 100 to 500 μm) on the discharge dynamics are investigated. Inside the tubes, while the topology of the bullets seems to be strongly dependent on the diameter, their velocity (on the order of 1 to 5 $\times$ 10^5 ms^{-1}) is only a function of the applied voltage. In ambient air, the air-plasma bullets propagate at a velocity of 1.25 $\times$ 10^5 ms^{-1}. Possible mechanisms for the propagation of air-plasma bullets in ambient air are discussed.

14:45

KW2 6 High pressure micro glow discharge: Detailed approach to gas temperature modeling* MOSTAFA MOBLI, TANVIR FAROUK, *Department of Mechanical Engineering, University of South Carolina* High pressure micro plasma discharge has been the center of interest in recent years, unlike low pressure discharges; gas heating is an important factor in these discharges. A Dirichlet temperature boundary condition (iso-thermal) which is the most commonly used, is unable to capture the cathode and anode wall temperature temporal changes, effects of materials thermal characteristics and also forces an artificial cooling of the discharge. To overcome this inadequacy a conjugate heat transfer (CHT) model has been implemented which is found to resolve the gas temperature predictions both in the volume and the electrode surfaces more accurately. The implemented CHT model increases the overall computational overhead due to resolution of the temperature field in the solid phase, hence a novel temperature boundary condition has been proposed that resolves a temporally evolving electrode surface temperature without implicitly solving the temperature in the solid phase. Comparison with the experimental results shows that these two new approaches are able to predict an agreeable gas temperature distribution. The effect of pressure on the discharge characteristics also has been studied.

*Work was supported by DARPA under Army Research Office (ARO) Grant No. W911NF1210007.

SESSION KW3: ELECTRON-MOLECULE COLLISIONS AND RELATED PROCESSES I

Wednesday Afternoon, 5 November 2014; Room: State D at 13:30; Leigh Hargreaves, California State University, Fullerton, presiding

Invited Papers

13:30

KW3 1 Electron attachment to fluorocarbon radicals

NICHOLAS SHUMAN, *Air Force Research Laboratory*

Most plasma environments contain populations of short-lived species such as radicals, the chemistry of which can have significant effects on the overall chemistry of the system. However, few experimental measurements of the kinetics of electron attachment to radicals exist due to the inherent difficulties of working with transient species. Calculations from first principles have been attempted, but are arduous and, because electron attachment is so sensitive to the specifics of the potential surface, their accuracy has not been established. Electron attachment to small fluorocarbon radicals is particularly important, as the data are needed for predictive modeling of plasma etching of semiconductor materials, a key process in the industrial fabrication of microelectronics. We have recently developed a novel flowing afterglow technique to measure several types of otherwise difficult to study plasma processes, including thermal electron attachment to radicals. Variable Electron and Neutral Density Attachment Mass Spectrometry (VENDAMS) exploits dissociative electron attachment in a weakly ionized plasma as a radical source. Here, we apply VENDAMS to a series of halofluorocarbon precursors in order to measure the kinetics of thermal electron attachment to fluorocarbon radicals. Results are presented for CF_2, CF_3, C_2F_5, C_2F_3, 1-C_3F_7, 2-C_3F_7, and C_3F_5 from 300 K to 900 K. Both the magnitude and the temperature dependences of rate coefficients as well as product branching between associative and dissociative attachment are highly system specific; however, thermal attachment to all species is inefficient, never exceeding 5% of the collision rate. The data are analyzed using a recently developed kinetic modeling approach, which uses extended Vogt-Wannier theory as a starting point, accounts for dynamic effects such as coupling between the electron and nuclear motions through empirically validated functional forms, and finally uses statistical theory to determine the fate of the highly excited anion intermediate formed during attachment. The kinetic modeling, along with complimentary data from electron beam measurements, is used to extrapolate the electron attachment rate coefficients to temperature and pressure regimes inaccessible to the experiment, including to non-thermal plasma conditions most relevant to plasma etching.

[1]P. Macko *et al.*, Int. J. Mass Spectrom. **233**, 299 (2004).
[2]R. Johnsen *et al.*, J. Phys. Chem. A **117**, 9477 (2013).

Contributed Papers

14:00

KW3 2 H_2-Assisted Ternary Recombination of H_3^+ with Electrons at 300 K* RAINER JOHNSEN, *University of Pittsburgh* PETR DOHNAL, PETER RUBOVIC, ABEL KALOSI, MICHAL HEJDUK, RADEK PLASIL, JURAJ GLOSIK, *Charles University Prague* Afterglow measurements in ionized He/Ar/H_2 gas mixtures at 300 K show that the recombination of H_3^+ ion with electrons is very strongly enhanced in the presence of molecular hydrogen. In the experiments the decay of H_3^+ ions was measured by near-infrared (NIR) absorption spectroscopy (SA-CRDS) [1]. Rather surprisingly, the H_2-assisted three-body recombination coefficient ($K_{H2} = (8.7 +/-1.5) \times 10^{-23}$ cm^6 s^{-1}) exceeds by more than two orders of magnitude the corresponding He-assisted coefficient ($K_{He} = (3.3 +/-0.7) \times 10^{-25}$ cm^6 s^{-1}) that we measured earlier [2]. Formation of faster recombining H_5^+ cluster ions does not play a significant role at temperature near 300 K. The ternary processes are found to saturate at high He and H_2 densities, suggesting that recombination proceeds by a two-step process, electron capture (with a rate coefficient $\alpha_F = (1.5 +/-0.1) \times 10^{-7}$ cm^3 s^{-1}) into a long-lived Rydberg state with an excited core, followed by collisional stabilization. While these findings provide a plausible explanation for some of the discrepancies between earlier afterglow measurements of H_3^+ recombination, the exact nature of these long-lived complexes, and their collisional interactions remain to be elucidated.

*This work was partly supported by GACR P209/12/0233, GACR 14-14649P, GAUK 692214.

14:15

KW3 3 Kinetics of ion-ion mutual neutralization* THOMAS M. MILLER, JUSTIN P. WIENS, NICHOLAS S. SHUMAN, ALBERT A. VIGGIANO, *Air Force Research Laboratory* We have measured rate coefficients for 87 mutual neutralization reactions between thermal energy anions and cations, a number of them as a function of temperature. In addition, in two cases we have observed a transfer ionization channel in which there is enough energy for the anion reactant to be doubly ionized, yielding a cation product rather than neutralization. We will summarize these results and note correlations, namely: (1) binary neutralization rate coefficients are primarily a function of the chemical nature of the system for atom-atom ionic pairs (with a wide range of rate coefficients), but quickly become dominated by physical aspects (i.e., relative velocity) as the number of atoms in the system increases. (2) Rate coefficients for atom-atom ionic pairs are well fit at 300 K by $k = 3 \times 10^{-4} R_x^{-3.15}$, where R_x is the curve crossing radius given by $R_x = 27.2/\Delta E$, with ΔE being the electron transfer energy released in the reaction. (ΔE in eV, R_x in Bohr, and k in cm^3/s.) (3) Rate coefficients for systems of more than 4 or 5 atoms are well described by $k = 2.7 \times 10^{-7} (T/300)^{-0.9} \mu^{-0.5}$. (T in K, and the reduced mass μ in amu.) (4) Triatomic systems have rate coefficients smaller than given by the expression in (3).

*Supported by the Air Force Office of Scientific Research, AFOSR 2303EP.

Invited Papers

14:30

KW3 4 Electron scattering measurements from molecules of technological relevance*

DARRYL JONES, *School of Chemical and Physical Sciences, Flinders University*

Biomass represents a significant opportunity to provide renewable and sustainable biofuels [1]. Non-thermal atmospheric pressure plasmas provide an opportunity to efficiently breakdown the naturally-resilient biomass into its useful subunits [2]. Free electrons produced in the plasma may assist in this process by inducing fragmentation though dissociative excitation, ionization or attachment processes [3]. To assist in understanding and refining this process, we have performed electron energy loss experiments from phenol (C_6H_5OH), a key structural building block of biomass. This enables a quantitative assessment of the excited electronic states of phenol. Differential cross sections for the electron-driven excitation of phenol have also been obtained for incident electron energies in the 20–250 eV range and over 3–90° scattering angles.

*DBJ acknowledges financial support provided by an Australian Research Council DECRA.

[1]A. J. Ragauskas *et al.*, Science **311**, 484 (2006).
[2]M. Benoit *et al.*, Angew. Chem. Int. Ed. **50**, 8964 (2011).
[3]E. M. de Oliveira *et al.*, Phys. Rev. A **86**, 020701(R) (2012).

SESSION LW1: PLASMA DIAGNOSTICS III
Wednesday Afternoon, 5 November 2014
Room: State EF at 15:30
Pascal Chabert, Laboratoire de Physique des Plasmas, presiding

Contributed Papers

15:30
LW1 1 Inductively-coupled plasmas in pure Cl, Oand mixtures: measurements of atoms, $Cl_xO_y$and electron densities MICKAËL FOUCHER, *LPP-CNRS UMR 7648* EMILE CARBONE, *CEA grenoble* JEAN-PAUL BOOTH, PASCAL CHABERT, *LPP-CNRS UMR 7648* LPP-PLASMAS FROIDS TEAM Inductively-coupled plasmas in Cl/O (often with HBr) are widely used in the microelectronics industry for the etching of silicon CMOS gates. Many simulations describing these plasmas (global and 2-dimensional fluid models such as HPEM) have been developed but experimental validation is sparse. This paper addresses this gap with a large quantity of experimental data in plasmas of Cl, Oand their mixtures. The plasma is excited by a 4-turn planar coil powered at 13.56 MHz through a dielectric window, and contained in a cylindrical anodized aluminium reactor (55 cm diameter, 10 cm high). Electron densities were measured with a microwave hairpin resonator. In all cases the electron density passes through a maximum with pressure. The ground-state O and Cl atom density was measured by Two-Photon Absorption Laser-Induced Fluorescence (TALIF) combined with specific absolute calibration techniques. Broad-band absorption spectroscopy was used to measure the density of Cland vibrationally excited Omolecules, excited state Cl atoms and a range of oxychlorides products. To our knowledge this is the first time that these oxychloride densities and vibrationally excited molecules have been measured in low-pressure plasmas.

15:45
LW1 2 Time evolution of spatial RF field profiles in a 100 MHz reactor BARTON LANE, *Tokyo Electron America* IKUO SAWADA, *Retired* PETER VENTZEK, COLIN CAMPBELL, *Tokyo Electron America* AKIRA KOSHIISHI, *Tokyo Electron Miyagi* We report here on time and space resolved magnetic and electric field strength measurements in a 100 MHz reactor. The reactor studied is a test bed reactor with a geometry which approximately mimics commercial reactors for semiconductor manufacturing. The magnetic fields were captured using a B-dot probe fashioned after the work of Miller *et al.* [1] Time traces at different radial locations are compared using time traces from a fixed pickup probe mounted on the VHF feed in order to obtain magnetic field profiles as a function of radius at different values of the VHF phase. The presence of standing waves and propagating waves are clearly seen. A rapid increase and collapse of the magnetic field at the core of the plasma takes place on a nsec time scale showing the physical origin of the higher harmonic waves seen in previous studies. The profiles show the effect of the non-linear evolution of the wave. The data is presented as an animated sequence of plots of the field strength vs radius. A double dipole probe was also used to measure the vertical component of the VHF field. These measurements confirm the picture given by the B dot probe.

[1]Miller, Barnat, Hebner, Paterson, and Holland, Plasma Sources Sci. Tech. **15**, 889 (2006).

16:00
LW1 3 Low pressure characteristics of the multipole resonance probe* RALF PETER BRINKMANN, JENS OBERRATH, *Ruhr-University Bochum* The term "Active plasma resonance spectroscopy" (APRS) denotes a class of related techniques which utilize, for diagnostic purposes, the natural ability of plasmas to resonate on or near the electron plasma frequency ω_{pe}. The basic idea dates back to the early days of discharge physics but has recently found renewed interest as an approach to industry-compatible plasma diagnostics: A radio frequent signal (in the GHz range) is coupled into the plasma via an antenna or probe, the spectral response is recorded (with the same or another antenna or probe), and a mathematical model is used to determine plasma parameters like the electron density or the electron temperature. When the method is applied to low pressure plasmas (of a few Pa and lower), kinetic effects must be accounted for in the mathematical model. This contribution studies a particular realization of the APRS scheme, the geometrically and electrically symmetric Multipole Resonance Probe (MRP). It is shown that the resonances of the MRP exhibit a residual damping in the limit $p \to 0$ which cannot be explained by Ohmic dissipation but only by kinetic effects.

*Supported by the German Federal Ministry of Education and Research (BMBF) in the framework of the PluTO project.

16:15
LW1 4 Diagnostics of Rotational Temperature and Mean Electron Energy Distribution of DC Glow Discharge Using Spectral Image Processing DAISUKE SHIMIZU, RYO SASAMOTO, TAKAO MATSUMOTO, YASUJI IZAWA, KIYOTO NISHIJIMA, *Fukuoka University* The non-thermal plasma has been used in various application fields of manufacturing industry such as surface reforming, plasma etching, deposited film forming. The gas temperature and electron energy in non-thermal plasma play a key role of production of active species. Therefore, it is essential to understand the properties of non-thermal plasma for effective plasma applications. In this study, the two-dimensional rotational temperature and mean electron energy distribution of DC glow discharge plasma under various air pressures were observed using spectral image processing. Rotational temperature distribution was estimated from the emission intensity ratio of head and tail of 2nd positive system band of N_2 (0, 2). On the other hand, mean electron energy was estimated from the emission intensity ratio of 2nd positive system band of N_2 (0, 2) and 1st negative system band of N_2^+ (0, 0). The each spectral images were taken by an ICCD camera with narrow band-path filters respectively. As a result, the dependences of rotational temperature and mean electron energy distribution in DC glow discharge on ambient air pressure were clearly observed using spectral image processing.

16:30
LW1 5 Laser Induced Fluorescence of the Iodine Ion WILLIAM HARGUS, *Air Force Research Laboratory, Edwards AFB, CA* Iodine (I_2) has been considered as a potential electrostatic spacecraft thruster propellant for approximately 2 decades, but has only recently been demonstrated. Energy conversion efficiency appears to be on par with xenon without thruster modification. Intriguingly, performance appears to exceed xenon at high acceleration potentials. As part of a continuing program for the development of non-intrusive plasma diagnostics for advanced plasma spacecraft propulsion, we have identified the I II $5d^5 D_4^o$ state as metastable, and therefore containing a reservoir of excited state ions suitable for laser probing. The $5d^5 D_4^o - 6p^5 P_3$ transition at 695.878 nm is convenient for diode laser excitation with the $5s^5 S_2^o - 6p^5 P_3$ transition at 516.12 nm as an ideal candidate for non-resonant fluorescence

collection. We have constructed a Penning type iodine microwave discharge lamp optimized for I II production for table-top measurements. This work demonstrates I II laser-induced fluorescence in a representative iodine discharge and will validate our previous theoretical work based on the limited available historical I II spectral data.

16:45
LW1 6 Picosecond-TALIF measurements of atomic oxygen in RF driven atmospheric pressure plasma jets* JEROME BREDIN, JAMES DEDRICK, KARI NIEMI, ANDREW WEST, ERIC WAGENAARS, TIMO GANS, DEBORAH O'CONNELL, *York Plasma Institute, University of York* Picosecond resolution is required for direct measurements, without assumptions, of radicals under the highly collisional environment of atmospheric pressure. Quenching of two-photon absorption laser induced fluorescence (TALIF) excited states is very efficient and the lifetime of approx. a few ns is in the order of a typical ns laser pulse width. To determine radical densities, challenges include knowing the quenching partners and calculating associated quenching rates to obtain the effective lifetime. Using ps-TALIF (32 ps pulse width) it is possible to resolve the lifetime and therefore avoid quenching rate calculations. Spatially resolved measurements in the plume of an RF atmospheric pressure plasma with O2 and dry air admixtures show that the excited state lifetime and ground state densities decrease at the extremities of the plume due to ambient air diffusion. The lifetime with dry air admixtures is longer than with O2 admixtures as oxygen is a more efficient quencher than nitrogen. Measurements in O2 admixtures show that the lifetimes obtained with ps-TALIF are shorter than those calculated. Consequently, either quenching through plasma produced species and/or three body collisions may play a role.

*The authors acknowledge support by the UK EPSRC EP/H003797/1 and EP/K018388/1.

17:00
LW1 7 Spectroscopic diagnostics of dusty plasmas KARIM OUARAS,* *LSPM - CNRS* GREMI - CNRS COLLABORATION,† INP GREIFSWALD COLLABORATION‡ The formation of carbon nanoparticles particles in low pressure magnetized hydrocarbon plasmas is investigated using infrared quantum cascade laser absorption spectroscopy (QCLAS), mass spectrometry (MS) and laser extinction spectroscopy (LES). Results showed that dust formation is correlated to the presence of a large amount of large positively charged hydrocarbon ions. Large negative ions or neutral species were not observed. These results, along with a qualitative comparison of diffusion and reaction characteristic, suggest that a positive ion may contribute to the growth of nanoparticles in hydrocarbon magnetized plasmas. Growth of carbon nanoparticles has been widely studied in RF plasma. Our aim is to complete these studies in different discharge system, in which the growth mechanisms may be different. In particular, we focus our work on dipolar ECR microwave discharge. The magnetic field of the plasma source is likely to trap carbon-containing charged particles and then modify the dust growth kinetics. In the present study the combination of these diagnostics gives us the tools to study the kinetics of plasma processes. In this way both qualitative and quantitative characteristics could be obtained. An outstanding role may be attributed to the positive ions in the monitored magnetized plasmas, whereas usually formation of dust is supposed driven by negative ions. In addition, we focus our work in tungsten nanoparticle in particular with LES, this noninvasive technique provide us the tool to follow the dynamics and concentration dust.

*K. Ouaras, L. Colina Delacqua, G. Lombardi, K. Hassouni, and X. Bonnin.
†M. Wartel.
‡J. Röpcke.

17:15
LW1 8 Resonance Frequencies of Curling Probe in Plasma: Surface Wave Analysis ALI ARSHADI, RALF PETER BRINKMANN, *Department for Electrical Engineering and Information Sciences, Ruhr University Bochum* Electron density is a crucial characteristic in reactive plasma sources determining the quality of material processing like etching. A recently invented plasma diagnostic probe called curling probe resonates in distinctive frequencies when it is embedded in the wall of the plasma reactor. The excited frequencies are studied for various electron densities. It has been demonstrated that the high-frequency (HF) volume wave resonances and the low-frequency (LF) surface wave (SW) resonances are predictable considering the wave propagation in plasma when it is diffracted on the curling probe. We consider the three dimensional diffraction of incident plane wave by a slot in an infinitely thin perfectly conducting screen located between dielectric and sheath. Our computations for LF resonances were published recently. The results are in a very good agreement with the FDTD analysis. Here it is demonstrated that the LF resonances are based on the SW propagation. We compare our result with the one comes from SW analysis and we prove that the LF resonances are not dependent on the length of probe. We generalized our study to be able to investigate the effect of sheath thickness and electron-neutral collisions which is not possible in the other theoretical and computational methods.

SESSION LW2: PLASMAS IN LIQUIDS
Wednesday Afternoon, 5 November 2014
Room: State C at 15:30
Peter Bruggeman, University of Minnesota, presiding

Contributed Papers

15:30
LW2 1 Advanced oxidation processes for wastewater treatment using a plasma/ozone combination system NOZOMI TAKEUCHI, YU KAMIYA, RYO SAEKI, KOSUKE TACHIBANA, KOICHI YASUOKA, *Tokyo Institute of Technology* Advanced oxidation process (AOP) using OH radicals is a promising method for the decomposition of persistent organic compounds in wastewater. Although many types of plasma reactors have been developed for the AOP, they are unsuitable for the complete decomposition of highly concentrated organic compounds. The reason for the incomplete decomposition is that OH radicals, particularly at a high density, recombine among themselves to form hydrogen peroxide. We have developed a combination plasma reactor in which ozone gas is fed, so that the generated hydrogen peroxide is reconverted to OH radicals. Pulsed plasmas generated within oxygen bubbles supply not only OH radicals but also hydrogen peroxide into wastewater. The total organic carbon (TOC) of the wastewater was more than 1 gTOC/L. The TOC values decreased linearly with time, and the persistent compounds which could not be decomposed by ozone were completely mineralized within 8 h of operation.

15:45
LW2 2 Simulation with power circuit by modeling of plasmas within bubble in water HAYATO OBO, NOZOMI TAKEUCHI,

KOICHI YASUOKA, *Tokyo Institute of Tech.* Plasma is used in water treatments such as the decomposition of persistent compounds and the generation of chemically active species. We have developed a new plasma reactor with 21 treatment holes and successfully achieved the decomposition of organofluoric compounds by generating 21 plasmas in water. The equivalent circuit model of plasma within bubbles in water consists of plasma and water resistance. A typical plasma model consists of a Zener diode and cannot be used to express the transient state of plasma. In the Zener diode model, therefore, plasma cannot be simulated with a power circuit. In this work, we have developed a new equivalent circuit that consists of an ideal switch, a diode, and water resistance to model the plasma. With the circuit elements used in our model, it is possible to perform simulation of plasmas by modeling the generation as well as the extinction of plasma with a high voltage power circuit. We confirmed that the simulated voltage and current waveforms of the reactor were coincident with the experimental result by applying the variation of a plasma parameter in the plasma model.

16:00

LW2 3 Physical and chemical interactions at the interface between atmospheric pressure plasmas and aqueous solutions ALEXANDER LINDSAY, BRANDON BYRNS, DETLEF KNAPPE, *North Carolina State University* DAVID GRAVES, *University of California Berkeley* STEVEN SHANNON, *North Carolina State University* Transport and reactions of charged species, neutrals, and photons at the interface between plasmas and liquids must be better quantified. The work presented here combines theoretical and experimental investigations of conditions in the gas and liquid phases in proximity to the interface for various discharges. OES is used to determine rotational and vibrational temperatures of OH, NO, and N_2^+; the relationship between these temperatures that characterize the distribution of internal energy states and gas and electron kinetic temperatures is considered. The deviation of OH rotational states from equilibrium under high humidity conditions is also presented. In contradiction with findings of other groups, high energy rotational states appear to become underpopulated with increasing humidity. In the aqueous phase, concentrations of longer-lived species such as nitrate, nitrite, hydrogen peroxide, and ozone are determined using ion chromatography and colorimetric methods. Spin-traps and electron paramagnetic resonance (EPR) are investigated for characterization of short-lived aqueous radicals like OH, O_2^-, NO, and $ONOO^-$. Finally, experimental results are compared to a numerical model which couples transport and reactions within and between the bulk gas and liquid phases.

16:15

LW2 4 Interaction of a plasma bullets with dielectric and liquid surface MARGUERITE DANG VAN SUNG MUSSARD, *LPP, Ecole Polytechnique* ANTOINE ROUSSEAU, *LPP, Ecole Polytechnique, CNRS* COLD PLASMA TEAM Recently, the physics of the propagation of a discharge inside a dielectric capillary tube in Helium working in a low frequency sine High Voltage was studied. It was shown that the bullet propagation is controlled by the memory effect of the deposited charges in the inner surface of the capillary [1]. Here, we focus on the physics of the interaction of bullets with liquid and/or dielectric surfaces. A 100–1000 Hz sinusoidal or a pulsed nanosecond high voltage is applied to a pin inside a dielectric tube in order to create a plasma bullet able to propagate in the tube and in the open air, at the end of the tube. We characterize the dynamics of the discharge, its propagation and its interaction with the liquid and dielectric phase, by electrical and optical diagnostics. The energy transfer from the capillary tube to the outer surface is studied as a function of the gap distance, applied voltage and liquid conductivity. A comparison is done between sine voltage and nanosecond pulse working conditions. Authors thank Emeric Foucher for experimental work and Labex Plas@Par for support.

[1]M. Dang Van Sung Mussard, O. Guaitella, and A. Rousseau, J. Phys. D: Appl. Phys. **46**, 302001 (2013).

16:30

LW2 5 Numerical simulation of plasma-induced electrolysis utilizing dc glow discharge* FUMIYOSHI TOCHIKUBO, NAOKI SHIRAI, SATOSHI UCHIDA, *Tokyo Metropolitan University* TATSURU SHIRAFUJI, *Osaka City University* In this work, we carried out one-dimensional numerical simulation of plasma-induced electrolysis, which consists of atmospheric pressure dc glow discharge and electrolyte solution connected in series. Grounded metal electrode is placed at the bottom of NaCl solution with 1 mm depth while powered electrode is placed at 1 mm above the solution surface. The gap is filled with helium. Continuity equations of charged species both in gas and in liquid were simultaneously calculated with Poisson's equation. Current continuity is considered at plasma-liquid interface. That is, hydrated electrons equivalent to electron flux from plasma, or H_2O^+ ions equivalent to positive ion flux from plasma are supplied in the liquid at plasma-liquid interface. The calculated gas-phase discharge structure is essentially the same as that between two metal electrodes. In front of the metal electrode in liquid, the electric double layer (EDL) with thickness of approximately 10 nm was formed to maintain the electrode reaction. However, the EDL was not formed at the liquid surface in contact with dc glow discharge, because charges are forcibly supplied from plasma to liquid. In other words, plasma-induced electrolysis is controlled at plasma-liquid interface by plasma.

*This work was partly supported by KAKENHI (Nos. 21110003 and 21110007).

16:45

LW2 6 Control of plasma-liquid interaction of atmospheric DC glow discharge using liquid electrode* NAOKI SHIRAI, RYUTA AOKI, AIHITO NITO, TAKUYA AOKI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* Atmospheric plasma in contact with liquid have a variety of interesting phenomena and applications. Previously, we investigated the fundamental characteristics of an atmospheric dc glow discharge using a liquid electrode with a miniature helium flow. We tried to control the plasma-liquid interaction by changing the plasma parameter such as gas species, liquid, and applied voltage. Sheath flow system enables another gas (N_2, O_2, Ar) flow to around the helium core flow. It can control the gas species around the discharge. When liquid (NaCl aq.) cathode DC discharge is generated, Na emission (588 nm) can be observed from liquid surface with increasing discharge current. Na emission strongly depends on the discharge current and liquid temperature. However, when Ar sheath flow is used, the intensity of Na becomes weak. When liquid anode DC discharge is generated, self-organized luminous pattern formation can be observed at the liquid surface. The pattern depends on existence of oxygen gas in gap. By changing the oxygen gas ratio in the gap, variety of pattern formation can be observed. The discharge in contact with liquid also can be used for synthesis of metal nanoparticles at plasma-liquid interface. Size and shape of nanoparticles depend on discharge gases.

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

17:00

LW2 7 Characteristics of micro plasma generated on the nanoscale electrode in water TOMONARI AOYAMA, *Department of Electronic Engineering, Tohoku University* HIDEMASA FUJITA, TAKEHIKO SATO, *Institute of Fluid Science, Tohoku University* TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University* Discharges in water are anticipated for various applications such as nano material processing, organic compounds degradation, and bio-medical treatment. Especially, for the bio-medical application, there is a demand to generate micro scale plasma which is smaller than a cell to have an effect only on the selected cell. In this work, the electrodes with curvature radius of less than 1 μm are used and the streamer development from the electrode tip is observed. To characterize the streamers from the electrode tip, the relations among the discharge time, voltage, current, shadowgraph imaging, and optical emission are investigated. The shadowgraph imaging has the maximum time resolution up to 5 ns at resolution of 12 pixel/μm using a high magnification lens and a high speed camera. In the shadowgraph imaging, the streamers are observed at the minimum pulse voltage amplitude of 4 kV. Prior to the streamer development, the precursor of the streamer is formed around the tip of the nanoscale electrode. The maximum size of the precursor region is found to be 20 μm which corresponds to the typical cell size. These results show the feasibility of affecting a specific cell with micro scale discharge.

17:15

LW2 8 Plasma Jet (V)UV-Radiation Impact on Biologically Relevant Liquids and Cell Suspension* H. TRESP, *ZIK plasmatis at INP Greifswald* R. BUSSIAHN, *INP Greifswald* L. BUNDSCHERER, *ZIK plasmatis at INP Greifswald* A. MONDEN, *ZIK plasmatis at INP Greifswald, TU Eindhoven* M.U. HAMMER, K. MASUR, *ZIK plasmatis at INP Greifswald* K.-D. WELTMANN, TH. V. WOEDTKE, *INP Greifswald* S. REUTER, *ZIK plasmatis at INP Greifswald* In this study the generation of radicals in plasma treated liquids has been investigated. To quantify the contribution of plasma vacuum ultraviolet (VUV) and ultraviolet (UV) radiation on the species investigated, three cases have been studied: UV of plasma jet only, UV and VUV of plasma jet combined, and the plasma effluent including all reactive components. The emitted VUV has been observed by optical emission spectroscopy and its effect on radical formation in liquids has been analyzed by electron spin resonance spectroscopy. Radicals have been determined in ultrapure water (dH_2O), as well as in more complex, biorelevant solutions like phosphate buffered saline (PBS) solution, and two different cell culture media. Various compositions lead to different reactive species formation, e.g. in PBS superoxide anion and hydroxyl radicals have been detected, in cell suspension also glutathione thiyl radicals have been found. This study highlights that UV has no impact on radical generation, whereas VUV is relevant for producing radicals. VUV treatment of dH_2O generates one third of the radical concentration produced by plasma-effluent treatment. It is relevant for plasma medicine because although plasma sources are operated in open air atmosphere, still VUV can lead to formation of biorelevant radicals.

*This work is funded by German Federal Ministry of Education a Research (BMBF) (Grant # 03Z2DN12+11).

SESSION LW3: ELECTRON-MOLECULE COLLISIONS AND RELATED PROCESSES II

Wednesday Afternoon, 5 November 2014; Room: State D at 15:30; Don Madison, Missouri S&T, presiding

Invited Papers

15:30

LW3 1 Tailoring Bond Cleavage in Gas-Phase Biomolecules by Low Energy Electrons*

SYLWIA PTASINSKA, *University of Notre Dame*

The high energy quanta of impinging radiation can generate a large number (about 5x10^4) of secondary electrons per 1 MeV of energy deposited. When ejected in condensed phase water, the kinetic energy distribution of these free or quasi-free electrons is peaked below 10 eV. Low energy electrons also dominate in the secondary emission from biomolecular targets exposed to different energies of primary radiation. Due to the complexity of the radiation-induced processes in the condensed-phase environment, mechanisms of secondary electrons induced damage in biomolecules (BM) still need to be investigated. However, based on results from theory and different experiments accumulated within the last decade, it is now possible to determine the fundamental mechanisms that are involved in many chemical reactions induced in isolated gas-phase biomolecules by low energy electrons. The central finding of earlier research was the discovery of the bond- and site- selectivity in the dissociative electron attachment (DEA) process to biomolecules. It has been demonstrated that by tuning the energy of the incoming electron we can gain control over the location of the bond cleavage. These studies showed the selectivity in single bond cleavage reactions leading to the formation of the dehydrogenated closed shell anion $(BM\text{-}H)^-$ or the complementary reaction leading to H^-. The loss of a hydrogen atom or an anion is fast compared with ring cleavage and the excision of heavier fragments and, hence, this reaction can compete efficiently with autodetachment. Moreover, site selectivity has been also observed in the metastable anion formation via the DEA process. Such delayed fragmentation was studied recently for the dehydrogenated closed-shell anion conversion into NCO^- upon DEA proceeded a few μ sec after electron attachment, indicating a rather slow unimolecular decomposition. Interestingly, site selectivity was observed in the prompt as well as the metastable NCO^- formation in DEA.

*The research described herein was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Basic Energy Sciences, Office of Science, United States Department of Energy through Grant Number DE-FC02-04ER15533.

Contributed Papers

16:00

LW3 2 Vibrational change by electron collision* STEVEN GUBERMAN, *Institute for Scientific Research* The vibrational change in molecular ions due to collisions with electrons can be a fast process. This has not been generally recognized until relatively recently. For a high rate constant, the process requires a resonance state intermediate that is either vibrationally quasidiscrete or continuous. These highly excited states are common at energies just above the neutral ionization potential. The ab initio calculation of vibrational change rate constants is reported for N2+, i.e. N2+(v) + e → N2+(v') + e. The calculations utilize accurate potential curves, electronic widths and the MQDT approach for the calculation of cross sections and rate constants. The rate constants are found to be comparable to those for dissociative recombination. Rate constants over a wide electron temperature range for the lowest 5 ion vibrational levels will be reported.

*Supported by NSF and NASA.

16:15

LW3 3 On Helium Anions in Helium Droplets: Interpreting Recent Experiments* ANDREAS MAURACHER, STEFAN E. HUBER, *Leopold-Franzens-Universitaet Innsbruck* Helium droplets provide an ideal environment to study elementary processes in atomic systems at very low temperatures. Here, we discuss properties of charged and neutral, atomic and molecular helium species formed in helium droplets upon electron impact. By studying their interaction with atomic ground state helium we find that He, He_2 and excited (metastable) He^{*-} are well bound within the helium droplet. In comparison, He^*, He_2^* and He_2^{*-} are found to be squeezed out due to energetic reasons. We also present the formation pathways of atomic and molecular helium anions in helium droplets. Transition barriers in the energetic lowest He^{*-} - He interaction potentials prevent molecule formation at the extremely low temperatures in helium droplets. In contrast, some excited states allow a barrier-free formation of molecular helium (anions). With these theoretical results at hand we can interpret recent experiments in which the resonant formation of atomic and molecular helium anions was observed. Furthermore, we give an outlook on the implications of the presence of these anionic species in doped helium droplets with regard to charge transfer reactions.

*Austrian Fund Agency (FWF, I 978-N20, DK+ project Computational Interdisciplinary Modelling W1227-N16)/Austrian Ministry of Science (BMWF, Konjunkturpaket II, UniInfrastrukturprogramm of the Focal Point Scientific Computing).

Invited Papers

16:30

LW3 4 Dynamical Studies of Resonant Electron-Molecule Collisions*

DANIEL SLAUGHTER,[†] *Lawrence Berkeley National Laboratory*

A unique capability of low-energy electrons is to break molecular bonds through low-energy resonant processes. We report a combined experimental and theoretical study on the dynamics following dissociative electron attachment (DEA) at low collision energies that induce ring-breaking in uracil. The experiments employ a DEA reaction microscope [1], consisting of a 3D momentum-imaging negative ion spectrometer, a pulsed low-energy electron gun and an effusive gas target. Building further upon a recently-established technique [2–5], fragment ion kinetic energy and angular distributions resulting from DEA are measured and compared with ab initio scattering calculations to reveal key aspects of the dynamics of the transient anion system. Recent experiments on other related systems will also be presented.

*Supported by Chemical Sciences, Geosciences and Biosciences division of BES/DOE.
†In collaboration with Yosuke Kuriyama, Yu Kawarai, Yoshiro Azuma, Sophia University; Carl Winstead, Vincent McKoy, California Institute of Technology; and Ali Belkacem, Lawrence Berkeley National Laboratory.

[1]Adaniya *et al.*, Rev. Sci. Inst. **83**, 023106 (2012).
[2]Slaughter *et al.*, Phys. Rev. A **87**, 052711 (2013).
[3]Moradmand *et al.*, Phys. Rev. A **88**, 032703 (2013).
[4]Haxton *et al.*, Phys. Rev. A **84**, 030701 (2011).
[5]Adaniya *et al.*, Phys. Rev. Lett. **103**, 233201 (2009).

Contributed Papers

17:00

LW3 5 Elastic electron scattering from carbon dioxide ALLAN STAUFFER, *York University* TAPASI DAS, RAJESH SRIVASTAVA, *Indian Institute of Technology - Roorkee* We have derived a method to obtain the spherically symmetric part of the static interaction between an electron and an arbitrary molecule represented by Gaussian wave functions [1]. Adding polarization-correlation and local exchange potentials provides a total potential that represents electrons scattering from the molecule averaged over all spatial orientations. We will present results for electron scattering from the linear molecule CO_2 using such a potential. Since this molecule has no permanent dipole moment, we expect our method to produce accurate results for elastic scattering. We will compare our results with existing experimental and theoretical data for this process to assess the accuracy of the method.

[1]Tapasi Das, A. D. Stauffer, and Rajesh Srivastava, Eur. Phys. J. D **684**, 102 (2014).

17:15

LW3 6 Cross sections and products of electron ionization of m-xylene, p-xylene and o-xylene CHARLES JIAO, *UES* STEVEN ADAMS, *Air Force Research Laboratory* Xylenes are contained in many jet fuels and are one of the components in surrogate mixtures for JP-8. In this study using Fourier-transform mass spectrometry to measure the electron ionization cross sections of m-xylene, p-xylene and o-xylene, it is found that the total cross sections of the three xylene isomers are approximately equal at low energies (<25 eV), and become slightly different at higher energies, reaching maxima of 2.24, 2.10 and 2.05 $\times 10^{-15}$ cm^2, respectively, at 80 eV. The electron ionization on these xylenes produces similar products, mainly the parent ion $C_8H_{10}^+$ and fragment species including ($C_8H_9^+ + H$), ($C_8H_7^+ + H + H_2$), ($C_7H_7^+ + CH_3$), ($C_6H_7^+ + C_2H_3$), ($C_6H_6^+ + C_2H_4$), and ($C_6H_5^+ + C_2H_5$). The results indicate that the major by-products of the electron ionization of xylenes are CH_3 and H. The latter is believed to play an important role in fuel ignition because it is involved in both chain branching and chain breaking steps, and it triggers the fuel oxidation.

SESSION MW1: POSTER SESSION II (17:30-19:30)
Wednesday Evening, 5 November 2014
Exhibit Exhibit Hall at 17:30

MW1 1 The viscosity cross section for electron scattering from the heavy noble gases ALLAN STAUFFER, *York University* ROBERT MCEACHRAN, *Australian National University* The viscosity cross section is defined in terms of the elastic differential cross section $\sigma(\theta)$ as $\sigma_v = \int_0^\pi (1-\cos^2\theta)\sin\theta\,\sigma(\theta)\,d\theta$ and appears in the Boltzmann equation for the electron distribution function in velocity space. If this distribution function is expanded in Legendre polynomials, the viscosity cross section arises from the third term. Normally, only the first two terms in this expansion are retained in the solution of the Boltzmann equation. We have recently published results for the elastic and momentum transfer cross section for electron scattering from the heavy noble gases (argon, krypton and xenon) using our complex, relativistic optical potential method which includes the effect of excitation and ionization channels on the elastic cross sections. We also provided simple analytic fits to these cross sections to aid in plasma modelling calculations. We will present similar results for the viscosity cross sections for these gases including fits using similar analytic functions. By including the third term in the expansion of the Boltzmann equation which depends on this cross section, an evaluation of the accuracy of the two-term solution can be made.

MW1 2 Single and double photoionization of atoms by n-photon absorption at low intensity laser fields: a Generalized Sturmian approach JUAN M. RANDAZZO, FLAVIO D. COLAVECCHIA, *Centro Atomico Bariloche, Argentina* GUSTAVO GASANEO, *Universidad Nacional del Sur, Bahia Blanca, Argentina* DARIO M. MITNIK, *IAFE, Buenos Aires, Argentina* LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* We apply the Generalized Sturmian approach for the study of single and double photoionization of atoms by n-photon absorption at low intensity laser fields. We start with the double photoionization of helium by absorption of a single photon. The three-body wave functions necessary for the calculations (the ground state of the helium atom, and the scattering wave function which contains the post-collisional dynamics after one photon absorption) are both expanded with spherical Generalized Sturmian Functions (GSF) [1]. Very accurate triple differential cross sections for single photon double ionization are obtained helium for 20 and 40 eV. If two or more photons are absorbed, we have to consider the corresponding wave functions which describe the spatial distribution in each stage. We will then consider the scattering solutions for n>1 analyzing the applicability of an iterative scheme with a focus on the computational requirements for each n.

[1]G. Gasaneo *et al.*, Adv. Quantum Chem. **67**, 153 (2013).

MW1 3 Molecular Dynamics simulation of Ru flattening by Gas Cluster Ion Beam MASAAKI MATSUKUMA, KAZUYOSHI MATSUZAKI, *Tokyo Electron Limited* KENJI INABA, RYUJI MIURA, AI SUZUKI, NOZOMU HATAKEYAMA, AKIRA MIYAMOTO, *Tohoku University* Noble metals such as platinum or ruthenium have been hardly used in the semiconductor devices in spite of their physical and electrical properties, because they were hard to process. High energy monomer ion beams which can cut hard materials may induce structural damages. A gas cluster ion beam (GCIB) consists of a few thousands of atoms or molecules and is accelerated up to several tens keV. GCIB is able to realize localized high energy deposition with low energy per components in the cluster. This means that each component in clusters cannot have enough energy to react with surface. On the other hand, the clusters with tens keV of kinetic energy may make a high reactive field at the hypocenter areas. In consequence it is expected that the GCIB irradiation should achieve the metal processing with low damage. Recently flattening of Ru thin films using GCIB is reported. We conducted molecular dynamics simulation of GCIB incident to Ru surface with the in-house interatomic potential models obtained based on the quantum chemical calculations and found that the internal degree of freedom of a cluster played important roles during the GCIB bombardment.

MW1 4 Comparison of analytical formulae and quantum calculations for differential cross sections in e-Ar* J.F.J. JANSSEN, *Einhdoven Tech. Univ.* O. ZATSARINNY, K. BARTSCHAT, *Drake Univ.* G.J.M. HAGELAAR, L.C. PITCHFORD, *CNRS and Univ. Toulouse* We have previously shown [1] that the fully *ab initio*, quantum mechanical *B*-spline *R*-matrix calculations of Zatsarinny and Bartschat for e-Ar cross sections yield accurate values of swarm parameters (transport and rate coefficients vs. reduced electric field strength, for uniform and constant E/N) when used as input in a Boltzmann solver. These comparisons were made by employing the calculated angle-integrated elastic momentum transfer and total inelastic cross sections (usually sufficient for accurate calculations of swarm parameters). The theory, however, also provides fully differential scattering information, which is now available for argon on the open access website LXCat (www.lxcat.net). In this presentation, we compare predictions from several previously proposed analytical formulae for the angular dependence of the cross sections with the quantum predictions. Such comparisons are of interest, for example, in PIC-MC simulations where, due to lack of information, some approximations about the angular dependence must be made and thus the use of analytical formulae is common.

*Work supported, in part, by the United States National Science Foundation (OZ and KB).

[1]L. Pitchford *et al.*, J. Phys. D **46**, 334001 (2013).

MW1 5 Electron collisions with cesium atoms – benchmark calculations and application to modeling an excimer-pumped alkali laser* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* NATALIA BABAEVA, MARK KUSHNER, *University of Michigan* The *B*-spline *R*-matrix (BSR) with pseudostates

WEDNESDAY EVENING \ MW1

method [1] was employed to describe electron collisions with cesium atoms. Over 300 states were kept in the close-coupling expansion, including a large number of pseudostates to model the effect of the Rydberg spectrum and the ionization continuum on the results for transitions between the discrete physical states of interest. Predictions for elastic scattering, excitation, and ionization for incident energies up to 200 eV are presented and compared to previous results [2,3] and experimental data. Our data were used to model plasma formation in the excimer-pumped alkali laser, XPAL, operating on the $Cs(6^2P_{3/2,1/2} \rightarrow (6^2S_{1/2})$ (852 nm and 894 nm) transitions. At sufficiently high operating temperature, pump power, and repetition rate, plasma formation in excess of 10^{14}–10^{15} cm^{-3} occurs. This may reduce laser output power by electron collisional mixing of the upper and lower laser levels [4].

*Work supported by the NSF under PHY-1068140, PHY-1212450, and the XSEDE allocation PHY-090031 (OZ, KB), and by the DoD High Energy Laser Multidisciplinary Research Initiative (NYB, MJK).

[1]O. Zatsarinny and K. Bartschat, J. Phys. B **46**, 112001 (2013).
[2]K. Bartschat and Y. Fang, Phys. Rev. A **62**, 052719 (2000).
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MW1 6 Electronic excitation of methanol by low-energy electrons LEIGH HARGREAVES, KEN VARELA, MURTADHA KHAKOO, *California State University Fullerton* CARL WINSTEAD, VINCE MCKOY, *California Institute of Technology* Differential and integral excitation cross section measurements for the 4 lowest-lying states of states for methanol will be presented, at electron energies between 9–20 eV. The data were obtained via electron-energy loss spectroscopy, incorporating a moveable aperture gas source, and applying a least squares data fitting routine to each spectra that separated overlapping contributions from discrete transitions. The results are compared with current theoretical calculations, as well as previously obtained data for water and preliminary results for excitation of ethanol.

MW1 7 A vortex line for K-shell ionization of a carbon atom by electron impact* S.J. WARD, *University of North Texas* J.H. MACEK, *University of Tennessee* We obtained using the Coulomb-Born approximation [1] a deep minimum in the TDCS for K-shell ionization of a carbon atom by electron impact for the electron ejected in the scattering plane [2]. The minimum is obtained for the kinematics of the energy of incident electron $E_i = 1801.2$ eV, the scattering angle $\theta_f = 4°$, the energy of the ejected electron $E_k = 5.5$ eV, and the angle for the ejected electron $\theta_k = 239°$. This minimum is due to a vortex in the velocity field. At the position of the vortex, the nodal lines of Re[T] and Im[T] intersect. We decomposed the CB1 T-matrix into its multipole components [1] for the kinematics of a vortex, taking the z'-axis parallel to the direction of the momentum transfer vector. The $m = \pm 1$ dipole components are necessary to obtain a vortex. We also considered the electron to be ejected out of the scattering plane and obtained the positions of the vortex for different values of the y-component of momentum of the ejected electron, k_y. We constructed the vortex line for the kinematics of $E_i = 1801.2$ eV and $\theta_f = 4°$.

*S.J.W. and J.H.M. acknowledge support from NSF under Grant No. PHYS- 0968638 and from D.O.E. under Grant Number DE-FG02-02ER15283, respectively.

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MW1 8 Out-of-plane (e, $2e$) measurements with 150 eV incident beam energy on He autoionizing levels* NICHOLAS L.S. MARTIN, *Univ of Kentucky* B.A. DEHARAK, *Illinois Wesleyan University* K. BARTSCHAT, *Drake University* In previous work we reported out-of-scattering-plane (e, $2e$) measurements and calculations for helium $2\ell 2\ell'$ autoionizing levels at 488 eV incident electron energy and scattering angle 20.5°. The results were presented as (e, $2e$) angular distributions energy-integrated over each level [1] and the detailed energy dependence of the recoil/binary peak ratio [2]. We have now begun similar measurements at 150 eV electron beam energy and scattering angle 39.2°. The geometry is then the same as for the earlier high energy experiments: ejected electrons are detected in a plane that contains the momentum transfer direction and is perpendicular to the scattering plane. The momentum transfer is 2.1 a.u., which is the same as in the earlier experiments. We will present preliminary data and compare the angular distributions with the high energy results.

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

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MW1 9 Experimental and Theoretical Fully differential cross sections for electron impact ionization of phenol molecules* ESAM ALI, *Missouri University of Science & Technology* D. JONES, G. SILVA, L. CHIARI, R. NEVES, *School of Chemical and Physical Sciences, Flinders University, Australia* M. LOPES, *Departamento de Física, UFJF, Juiz de Fora, MG, Brazil* M. BRUNGER, *School of Chemical and Physical Sciences, Flinders University, Australia* C. NING, *Tsinghua University, Beijing 100084, People's Republic of China* D. MADISON, *Missouri University of Science & Technology* Experimental and theoretical Fully Differential Cross Sections (FDCS) are presented for 250 eV electron impact ionization of the highest and next highest occupied molecular orbitals (HOMO and NHOMO). Theoretical results are compared with experiment for in plane scattering with projectile scattering angles of 5°, 10°, and 15°. Different theoretical models are examined - the molecular 3 body distorted wave (M3DW), and the distorted wave Born approximation (DWBA), with the effects of the post collision interaction (PCI) treated either exactly or with the Ward-Macek approximations. These approximations show good agreement with experimental data for binary peaks. However, for the recoil peak region, experiment finds a noticeable peak while theory predicts no peak. No recoil peak suggests no (or very weak) nuclear scattering, so we have investigated the importance of nuclear scattering by moving the nuclei closer to the center of mass.

*Work supported by NSF and the XSEDE.

MW1 10 Single electron impact ionization of the methane molecule MAMMAR BOUAMOUD, *University Center of Naama, 45000 Naama, Algeria* MOHAMMED SAHLAOUI, *Ecole Préparatoire En Sciences Et Technique de Tlemcen* NOUR EL HOUDA BENMANSOUR, *Laboratoire de Physique Théorique de Tlemcen* ATOMIC AND MOLECULAR COLLISIONS TEAM Triply differential cross sections (TDCS) results of electron-impact ionization of the inner $2a_1$ molecular orbital of CH_4 are presented in the framework of the Second Born Approximation and compared with the experimental data performed in coplanar asymmetric geometry. The cross sections are averaged on the random orientations of the molecular target for accurate comparison with experiments and are compared also with the theoretical calculations of the Three Coulomb wave (3CW) model. Our results are in good agreement with experiments and 3CW results in the binary peak. In contrast the Second Born Approximation yields a significant higher values compared to the 3CW results for the recoil peak and seems to describe suitably the recoil region where higher order effects can occur with the participation of the recoiling ion in the collision process.

MW1 11 Single photoionization of many electron atoms and molecules: a Sturmian approach. CARLOS M. GRANADOS CASTRO, LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* DARIO M. MITNIK, *IAFE, Buenos Aires, Argentina* GUSTAVO GASANEO, *Universidad Nacional del Sur, Bahia Blanca, Argentina* The Sturmian approach, using Generalized Sturmian Functions (GSF), has been applied successfully for the study of several atomic ionization processes [1]. The extension of the method to molecular systems is under development, and is the subject of the present contribution. As a first step, in order to test our methodology, we started with some atomic systems and calculated the photoionization cross section using the one-active electron approximation together with model potentials. We solved the time-independent, first-order perturbative, Schrödinger equation; the scattering wave function is expanded in GSF. Having validated our approach and computer codes, we then studied the photoionization of molecules, such as CH_4, using a similar method. After considering initially an angular-averaged model potential, we then used a non-central one leading to a set of angular-coupled of equations. The scattering wave function is again expanded in a GSF basis set, but this time with many different angular momenta. In order to take into account the random orientation of the molecule, an angular average over all the possible spatial orientation of the molecule is finally performed. The calculated cross sections are compared with theoretical and experimental data (see [2] and references therein).

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MW1 12 Cross Sections and Transport Properties of BR⁻ Ions in AR* JASMINA JOVANOVIC, *Faculty of Mechanical Engineering, University of Belgrade* VLADIMIR STOJANOVIC, ZORAN RASPOPOVIC, ZORAN PETROVIC, *Institute of Physics, University of Belgrade* We have used a combination of a simple semi-analytic theory - Momentum Transfer Theory (MTT) and exact Monte Carlo (MC) simulations to develop Br^- in Ar momentum transfer cross section based on the available data for reduced mobility at the temperature $T = 300$ K over the range 10 Td $\leqslant E/N \leqslant$ 300 Td. At very low energies, we have extrapolated obtained cross sections towards Langevin's cross section. Also, we have extrapolated data to somewhat higher energies based on behavior of similar ions in similar gases and by the addition of the total detachment cross section that was used from the threshold around 7.7 eV. Relatively complete set was derived which can be used in modeling of plasmas by both hybrid, particle in cell (PIC) and fluid codes. A good agreement between calculated and measured ion mobilities and longitudinal diffusion coefficients is an independent proof of the validity of the cross sections that were derived for the negative ion mobility data. In addition to transport coefficients we have also calculated the net rate coefficients of elastic scattering and detachment.

*Author acknowledge Ministry of Education, Science and Technology, Proj. Nos. 171037 and 410011.

MW1 13 Limitation of the local approximation for EDF determination on the periphery of the high pressure plasmas* KIRILL KAPUSTIN, MIKHAIL KRASILNIKOV, ANATOLY KUDRYAVTSEV, *St. Petersburg State University* Local approximation is widely used for the calculation of electron distribution function (EDF). In this approximation, terms which correspond to spatial gradients and ambipolar electric fields in a Boltzmann kinetic equation can be omitted, and EDF can be factorized in a product of electron density, which depends on radius and time and on part of EEDF, which depends on kinetic energy. In this case, EEDF is a function of local parameters such as heating (current-carrying) electric field, gas temperature, density of excited particles etc. These simplifications of calculations of the kinetic equation make this approximation widely used. In this work, physical formation mechanisms of EEDF in a high pressure positive column glow discharge are discussed. It is shown that criterion of applicability of local approximation depends not only on ratio between energy relaxation length and characteristic plasma dimension but also on ratio between heating and ambipolar electric fields. So that, in the gas periphery where ambipolar electric field becomes larger then axial electric field, the local approximation for EEDF is not valid even at a high pressures.

*This work was supported by RSCF and SPbSU.

MW1 14 Monte Carlo simulation of electrons in dense gases* WADE TATTERSALL, *Australian National University* GREG BOYLE, DANIEL COCKS, *James Cook University* STEPHEN BUCKMAN, *Australian National University* RON WHITE, *James Cook University* We implement a Monte-Carlo simulation modelling the transport of electrons and positrons in dense gases and liquids, by using a dynamic structure factor that allows us to construct structure-modified effective cross sections. These account for the coherent effects caused by interactions with the relatively dense medium. The dynamic structure factor also allows us to model thermal gases in the same manner, without needing to directly sample the velocities of the neutral particles. We present the results of a series of Monte Carlo simulations that verify and apply this new technique, and make comparisons with macroscopic predictions and Boltzmann equation solutions.

*Financial support of the Australian Research Council.

MW1 15 Electron swarm transport coefficients in mixtures of H2O with He and Ar: Experiment and Boltzmann equation calculations* JAIME DE URQUIJO, *Universidad Nacional Autónoma de México* E. BASURTO, *None* A.M. JUAREZ, *Universidad Nacional Autónoma de México* KEVIN NESS, ROBERT ROBSON, *James Cook University* MICHAEL BRUNGER, *Flinders University* RON WHITE, *James Cook University* The drift velocity of electrons in mixtures of gaseous water with helium and argon are measured over the range of reduced electric fields from 0–300 Td using a pulsed-Townsend technique. Small admixtures of water to both helium and argon are found to produce negative differential conductivity (NDC), despite NDC being absent from the pure gases. Comparison of the measured drift velocities with those calculated from a multi-term solution of Boltzmann's equation provides a further discriminative assessment on the accuracy and completeness of electron water vapour cross-sections.

*Funding acknowledgements: ARC, Mexican govt (PAPIIT IN 111014).

MW1 16 Transport properties derived from ion-atom collisions: ^{6}Li-^{6}Li$^+$ and ^{6}Li-^{7}Li$^+$ Cases* MONCEF BOULEDROUA, *Faculte de Medecine and Laboratoire de Physique des Rayonnements, Badji Mokhtar University, Annaba, Algeria* FOUZIA BOUCHELAGHEM, *Physics Department, Badji Mokhtar University, Annaba, Algeria* LPR TEAM This investigation treats quantum-mechanically the ion- atom collisions and computes the transport coefficients, such as the coefficients of mobility and diffusion. For the case of lithium, the calculations start by determining the gerade and ungerade potential curves through which ionic lithium approaches ground lithium. Then, by considering the isotopic effects and nuclear spins, the elastic and charge-transfer cross sections are calculated for the case of ^{6}Li$^+$ and ^{7}Li$^+$ colliding with ^{6}Li. Finally, the temperature-dependent diffusion and mobility coefficients are analyzed, and the results are contrasted with those obtained from literature. The main results of this work have been recently published in [1].

*This work has been realized within the frames of the CNEPRU Project D01120110036 of the Algerian Ministry of Higher Education.

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MW1 17 Positron cooling by vibrational and rotational excitation of a molecular gas* M.R. NATISIN, J.R. DANIELSON, C.M. SURKO, *University of California, San Diego* A better understanding of low energy positron-molecule collisions and thermalization processes will aid in the development of novel experimental techniques and technology. In particular, cryogenic positron plasmas would allow the creation of positron beams with significantly higher energy resolution than currently available, enabling the study of scattering features and annihilation processes not measurable using current techniques [1]. Measurements of positron temperature as a function of time are presented when a positron gas, confined in an electromagnetic trap at an elevated temperature ($\geqslant$1200 K), is cooled by interactions with the 300 K molecular gases CF_4, N_2 and CO. A simple model describing positron thermalization by coupling to vibrational and rotational modes is also presented and used to make cooling-rate predictions calculated in the Born approximation. Comparisons to the measured positron cooling-rate curves permit estimates of the magnitudes of the relevant cross sections. Positron cooling rates are compared for these gases at 300 K, and estimates of their effectiveness in cooling positrons to cryogenic temperatures is discussed.

*Work supported by NSF Grant PHY 10-68023.

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MW1 18 Two-Electron Systems in Generalized Exponential Cosine Screened Coulomb Potentials KARINA V. RODRIGUEZ, *Universidad Nacinal del Sur, Bahia Blanca, Argentina* LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* DARIO M. MITNIK, *IAFE, Buenos Aires, Argentina* We look at the ground state of two-electron systems placed in a dense quantum plasma environment where the three interactions between two particles of charges z_i and z_j placed at a distance r_{ij} can be described by exponential-cosine-screened Coulomb potential (ECSCP) [1] $V(r_{ij}) = z_i z_j \exp(-\lambda r_{ij}) \cos(\delta r_{ij})/r_{ij}$ where λ and δ are two positive real screening parameters related to the plasma frequency. The first calculations of the ground and first excited states of H^-, He and Li^+ where all three interactions between pairs of particles were represented by the same ECSCP, and with $\lambda = \delta$, were recently reported [2,3]. In the present work we show results for two-electron systems for which the interactions are described by generalized ECSCP with unequal parameters. Our calculations are performed with a rather versatile Configuration Interaction approach (see [3] and references therein), with correlated basis functions which explicitly depend on the three interparticle distances and which respect exactly all three cusp conditions.

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MW1 19 A particle-in-cell/Monte Carlo simulation of a dual frequency capacitively coupled chlorine discharge SHUO HUANG, *University of Michigan - Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University* JON TOMAS GUDMUNDSSON, *Science Institute, University of Iceland* The effect of the control parameters of both the high and low frequency sources on a dual frequency capacitively coupled chlorine discharge is investigated using a hybrid approach consisting of a particle-in-cell/Monte Carlo simulation and a volume averaged global model. The dependence of the plasma parameters such as particle density, effective electron temperature, electron energy probability function and ion energy and angular distributions for both Cl^+ and Cl_2^+ ions, on the discharge pressure, driving frequency, driving current density and secondary electron emission, is systematically investigated. As the low-frequency current density is increased the flux of Cl_2^+ ions to the surface increases only slightly while the average energy of Cl_2^+ ions to the surface increases almost linearly with increasing low-frequency current, which shows possible independent control of the flux and energy of Cl_2^+ ions by varying the low-frequency current in a dual frequency capacitively coupled chlorine discharge. Besides, as the high frequency current increases, the electron heating is enhanced in the sheath region and diminished in the bulk region, showing a transition of the electron heating from the drift-ambipolar mode to the α mode.

MW1 20 Generalized Analytical Model for the Radio-Frequency Sheath UWE CZARNETZKI, *Ruhr-University Bochum, Institute for Plasma and Atomic Physics* An analytical model for the planar radio frequency (RF) sheath in capacitive discharges is developed based on the applied RF voltage as the boundary condition. The model applies to all kind of waveforms for the applied RF voltage, includes both sheaths in a discharge of arbitrary symmetry, and allows for an arbitrary degree of ion collisionallity in the sheaths (charge-exchange collisions). Further, effects of the finite floating potential during sheath collapse are included. The model can even be extended to electronegative plasmas with low bulk conductivity. The individual sheath voltages, the self-bias, and the RF floating potentials are explicitly calculated by a voltage balance equation using a cubic-charge voltage relation for the sheaths. In particular, the RF-phase as a function of the sheath voltage is determined. This is an input for a single second order non-linear integro-differential equation which is governing the ion flow velocity in the sheath [1]. Fast numerical integration is straight forward and in many cases approximate analytical solutions can be obtained. Based on the solution for the ion flow velocity, densities, electric fields, currents, and charge-voltage relations are calculated. Further, the Child-Langmuir laws for the collisionless as well as the highly collisional case are derived. Very good agreement between model and experiments is obtained.

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MW1 21 Experimental Study of Sheath Voltage Scaling Laws in Asymmetric RF Capacitive Discharges* MILKA NIKOLIC, JANARDAN UPADHYAY, LEPSHA VUSKOVIC, SVETOZAR POPOVIC, *Old Dominion University, Physics Department, Center for Accelerator Science* Asymmetric radio frequency (RF) capacitive discharges have been attracting a continuous interest in ongoing research on complex shaped, three dimensional niobium superconducting radio frequency (SRF) cavities. To increase their performance, the SRF cavities can be etched by capacitively coupled RF discharges, a technology already used in semiconductor industry. Since the SRF performance parameters depend highly on plasma properties, we have studied the effects of different pressure, power and inner and outer electrode area ratio on the sheath voltage scaling laws in the finite length coaxial symmetry RF capacitive discharge, treated originally in [1]. The experimental set up used in this study consists of two finite-length cylindrical coaxial electrodes, the inner RF powered electrode and the outer grounded electrode. We performed the experiment in Ar and in 15% Cl diluted with Ar mixture at pressure range 0.0375–0.45 Torr and applying the powers from 25–200 W. The results are presented in the form of asymmetric sheath voltage scaling law.

*Supported by DOE under Grant No. DE-SC0007879. J.U. acknowledges support by JSA/DOE via DE-AC05-06OR23177.

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MW1 22 Ion velocity distribution function measurements in a dual-frequency rf sheath* NATHANIEL MOORE, WALTER GEKELMAN, PATRICK PRIBYL, *UCLA Department of Physics* YITING ZHANG, MARK KUSHNER, *Electrical Engineering and Computer Science, U. Michigan* Ion dynamics are investigated in a dual-frequency rf sheath above a 300 mm diameter biased silicon wafer in an industrial inductively coupled (440 kHz, 500 W) plasma etch tool. Ion velocity distribution (IVD) function measurements in the argon plasma are taken using laser induced fluorescence (LIF). Planar sheets of laser light enter the chamber both parallel and perpendicular to the surface of the wafer in order to measure both parallel and perpendicular IVDs at thousands of spatial positions. A fast (30 ns exposure) CCD camera measures the resulting fluorescence with a spatial resolution of 0.4 mm. The dual-frequency bias on the wafer is comprised of a 2 MHz low frequency (LF) bias and an adjustable 10–20 MHz high frequency (HF) bias. The bias voltages may be switched on and off (f_{rep} up to 1 kHz, duty cycle 10–90%). Several different bias and timing combinations were tested. Ion energy distribution function and ion flux measurements for each case are compared. For the LF case (no HF), the IVD was found to be uniform to within 5% across the wafer. IVDs as a function of phase of the LF bias were also measured. The LF experimental results are compared with simulations specifically designed for this particular plasma tool.

*Work supported by the NSF and DOE.

MW1 23 Capacitively coupled dc/rf discharges driven by arbitrary linear circuits JOHN CARY, *University of Colorado and Tech-X Corporation* MING-CHIEH LIN, C. ZHOU, DAVID SMITHE, *Tech-X Corporation* We have developed a method for computing the system of an arbitrary linear circuit coupled to a capacitively coupled plasma discharge. The method relies on the known method of separation of the vacuum and plasma generated fields for the discharge. It is time centered and implicit in the circuit quantities, thus guaranteeing second-order accuracy in time. This method has been implemented in the VSim engine (Vorpal). Numerical verification of the order of accuracy will be shown.

MW1 24 Observation of Transient Electric Fields in Particle-in-Cell Simulation of Capacitively Coupled Discharges SARVESHWAR SHARMA, SANJAY KUMAR MISHRA, PREDHIMAN KAW, *Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India* The analytical prediction of the presence of transient electric field regions between the bulk plasma and sheath edge in radio frequency capacitively coupled plasma (RF-CCP) discharges has been reported by Kaganovich [PRL **89**, 265006 (2002)]. In this paper we have used the semi-infinite particle-in-cell (PIC) simulation technique to verify the theoretical prediction for the existence of transient electric field in the linear regime; it is shown that the *PIC* simulation results are in good agreement with the results predicted by analytical model in this regime. It is also demonstrated that the linear theory overestimates the transient electric field as one moves from linear to weakly nonlinear regime. The effect of applied *RF*current density and electron temperature on evolution of transition field and phase mixing regime has been explored.

MW1 25 Investigation of self-excited plasma series resonance oscillations in multi-frequency capacitive discharges EDMUND SCHUENGEL, JULIAN SCHULZE, *Department of Physics, West Virginia University, Morgantown, WV 26506* IHOR KOROLOV, ARANKA DERZSI, ZOLTÁN DONKÓ, *Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary* The self-excitation of plasma series resonance (PSR) oscillations is a dominant feature in the current of asymmetric capacitively coupled radio-frequency discharges. The asymmetry can be caused by an asymmetry of the chamber geometry and/or that of the applied voltage waveform. We study the self-excitation of the PSR in a geometrically symmetric, electrically asymmetric capacitive argon discharge using PIC/MCC simulations as well as an analytical model. The results show that increasing the number of subsequent harmonics in the driving voltage waveform enhances the asymmetry and, therefore, leads to a significant increase of the current amplitude of higher harmonics, which are generated due to the nonlinearities of the sheaths. These high-frequency resonance oscillations between the capacitive sheaths and the inductive plasma bulk can only be reproduced correctly by the analytical model, if the cubic sheaths charge-voltage relation and the temporal modulation of the bulk length and electron density within the RF period are taken into account. Furthermore, we demonstrate that the nonlinear electron resonance heating (NERH) associated with the presence of PSR oscillations significantly contributes to the total electron heating and causes a spatial asymmetry of the ionization.

MW1 26 Control of ion energy distributions in capacitive RF discharges using customized voltage waveforms EDMUND SCHUENGEL, JULIAN SCHULZE, *Department of Physics, West Virginia University, Morgantown, WV 26506* IHOR KOROLOV, ARANKA DERZSI, ZOLTÁN DONKÓ, *Institute for Solid State*

Physics and Optics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary The flux and energy distribution of ions flowing onto the substrate in capacitive radio-frequency discharges is vitally important for the plasma surface interaction. Therefore, controlling and optimizing the shape of the ion flux-energy distribution (IED) allows for an improvement of various plasma surface processing applications. Recently, separate control of the mean energy and the total flux of ions has been achieved via the Electrical Asymmetry Effect. Here, we study the control of the IED shape in capacitively coupled radio-frequency discharges by applying customized voltage waveforms to the powered electrode. Data obtained from PIC/MCC simulations in helium at low pressures show that the dominant features in the shape of the IED result from the energy gain of ions flowing into the sheath and ions created in the sheath (in ion neutral collisions) in the periodically oscillating sheath electric field. The high-energy component of the IED is determined by ions flowing into the sheath, whereas ions created within the sheath lead to peaks in the IED at lower energies. We demonstrate, how the shape of the high-energy component as well as the position (energy) and height (flux) of the peaks can be controlled by varying the phases and amplitudes of the multiple applied frequencies.

MW1 27 Transition of Plasma Electrons from Anisotropy to Isotropy at Beginning of the Pulsed Discharges HYO-CHANG LEE, CHIN-WOOK CHUNG, *Hanyang University* We present experimental studies on the transition of plasma electrons from anisotropy to isotropy at beginning of the pulsed discharges. The electron energy probability functions (EEPFs) are obtained from the first derivate of the measured I-V curve at planar type Langmuir probes. Strong anisotropy is found depending on the probe direction at the first stage of the low pressure pulsed plasma. The anisotropy of the electrons is transited into isotropy on the EEPF. This study may provide fundamental understanding of both the electron acceleration via wave-electron interaction and the electron thermal transport in plasma discharges.

MW1 28 E-H transition and Hysteresis in Radio-Frequency Inductively Coupled Plasmas HYO-CHANG LEE, CHIN-WOOK CHUNG, *Hanyang University* We present both experimental and theoretical studies of E-H transition and hysteresis in radio-frequency inductive discharges. It is found that the hysteresis is significantly affected by nonlinearity of the plasma with the modification of electron energy distribution (EED). This kind of hysteresis is also observed in various plasma discharges with powers, pressures, and magnetic field where EEDs are evolved.

MW1 29 Comprehensive Plasma Diagnostics of Oxygen ICP* THOMAS WEGNER, CHRISTIAN KÜLLIG, JÜRGEN MEICHSNER, *University of Greifswald* A planar inductively coupled 13.56 MHz discharge (ICP) in pure oxygen was studied using comprehensive plasma diagnostics. In particular the 160 GHz Gaussian beam microwave interferometry, the Langmuir probe technique, the phase resolved optical emission and VUV absorption spectroscopy were applied. During the transition from the capacitive (E-) to the inductive (H-) mode all plasma parameter are changed. The E-mode at low electron density and high electron temperature is characterized by high electronegativity. The gas temperature is comparable to room temperature and the molecular oxygen ground state and metastable state ($O_2(a^1\Delta_g)$) density are not significantly changed with increasing RF power in the E-mode. During the transition into the H-mode the electron density increases over two orders of magnitude whereas the electron temperature decreases to about the half of the E-mode. The heating mechachnisms change from the rf sheath heating and electrical field reversal in the E-mode to two excitation rate patterns in the first and second half of the RF cycle. In the H-mode, the electronegativity is strongly reduced, the gas temperature and the metastable density are increased by a factor of about two.

*Funded by the DFG CRC/Transregio 24, Project B5.

MW1 30 Experimental observation of transit time resonance heating through electron energy distribution function measurement in a low pressure inductively coupled plasma HYUN-JU KANG, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* The maximum electron heating by transit time resonance is related to the driving frequency and the skin depth. In this study, electron energy distribution functions (EEDFs) were measured at various frequencies (8 MHz, 10 MHz, 13,56 MHz) and powers in a low-pressure inductively coupled plasma. It was observed that the heated electron energy on the EEDFs is shifted toward lower energy, as the frequency decreases or the power increases.

MW1 31 Simulation of Plasma Characteristics for Inductively Coupled Argon Plasma Using Dual-Frequency Antennas* XUE-CHUN LI, XIAO-YAN SUN, YOU-NIAN WANG, *Dalian University of Technology* A large-area wafer size is necessary for plasma processing in the micro-electronics industry. However, it is one of the most important issues to obtain uniform plasma over a large-area substrate in addition to high-density plasmas for the plasma processing. Recently, the experimental study on the dual-frequency inductively coupled plasma (ICP) has been reported as a mean of improving the plasma uniformity over the large-area substrate [1]. In this work, we develop a self-consistent method combined with the electromagnetic theory and fluid model to simulate the plasma characteristics for dual-frequency inductively coupled argon plasma. In the model, the ICP source consists of two planar-spiral coils. We investigate the plasma uniformity problem by adjusting the parameters of the two coils, such as the RF current, the position of the coils and the RF frequency ratio. It was found that the uniformity of the ion density over the wafer is improved with dual-frequency antennas comparing with a single-frequency antenna. The plasma uniformity increases when the coils are located farther from the centre of the ICP source. It is consistent with the experimental study.

*This work was supported by the National Natural Science Foundation of China (No. 11175034, No. 11075029).

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MW1 32 Discharge Characteristic of VHF-DC Superimposed Magnetron Sputtering System* HIROTAKA TOYODA, YUSHI FUKUOKA, TAKASHI FUKUI, NORIHARU TAKADA, KENSUKE SASAI, *Nagoya University* Magnetron plasmas are one of the most important tools for sputter deposition of thin films. However, energetic particles from the sputtered target such as backscattered rare gas atoms or oxygen negative ions from oxide targets sometimes induce physical and chemical damages as well as surface roughening to the deposited film surface during the sputtering processes. To suppress kinetic energy of such particles, superposition of RF or VHF power to the DC power has been investigated. In this study, influence of the VHF power superposition on the DC target voltage, which is important factor to determine kinetic energy of high energy particles, is investigated. In the study, 40 MHz VHF power was superimposed to an ITO target and decrease in the target DC voltage was measured as well as deposited film deposition properties such as deposition rate or electrical conductivity. From systematic measurement of the target voltage, it was revealed that the target voltage can be determined by a very simple parameter, i.e., a ratio of VHF power to the total input power (DC and VHF powers) in spite of the DC discharge current.

*Part of this work was supported by ASTEP, JST.

MW1 33 Carbon Multicharged Ion Generation from Laser Plasma* OGUZHAN BALKI, HANI E. ELSAYED-ALI, *Old Dominion Univ* Multicharged ions (MCI) have potential uses in different areas such as microelectronics and medical physics. Carbon MCI therapy for cancer treatment is considered due to its localized energy delivery to hard-to-reach tumors at a minimal damage to surrounding tissues. We use a Q-switched Nd:YAG laser with 40 ns pulse width operated at 1064 nm to ablate a graphite target in ultrahigh vacuum. A time-of-flight energy analyzer followed by a Faraday cup is used to characterize the carbon MCI extracted from the laser plasma. The MCI charge state and energy distribution are obtained. With increase in the laser fluence, the ion charge states and ion energy are increased. Carbon MCI up to C^{+9} are observed along with carbon clusters. When an acceleration voltage is applied between the carbon target and a grounded mesh, ion extraction is observed to increase with the applied voltage.

*National Science Foundation.

MW1 34 Energy Distribution of Aluminum Multicharged Ions Generated from Laser Plasma MD HAIDER SHAIM, ALEXEY BUGAYEV, HANI E. ELSAYED-ALI, *Department of Electrical and Computer Engineering and the Applied Research Center, Old Dominion University, Norfolk, Virginia 23529, USA* Multicharged ion sources are an emerging tool for nanoprocessing and nanofabrication. The higher charge state of multicharged ions has significant potential energy equal to the sum of ionization energies of stripped electrons. Multicharged ion interaction with solids involves the release of this potential energy that causes electronic exchange interaction along with the electronic excitation. We report on measurement of aluminum multicharged ion energy distribution generated by laser ablation of an aluminum target. A Q-switched Nd:YAG laser is used to ablate the aluminum target in an ultrahigh vacuum while an electrostatic time-of-flight spectrometer is used to detect the laser-generated multicharged ions. An increase in the ions' signal and generation of higher charge state is observed with the increase of laser ablation energy. The energy distribution of ions for increasing laser fluence shows an increase in the ion energy along with narrowing of the distribution. Applying an accelerating voltage to the aluminum target increases the charge extraction and the energy of multicharged ions. Angular distribution of the multicharged ions is dependent on the ion charge state. Multicharged ions up to Al^{+4} are detected.

MW1 35 Optical Studies of Sputtering in Magnetically Enhanced Helium Discharges* JAMES E. LAWLER, THOMAS J. FEIGENSON, *Univ of Wisconsin, Madison* TIMOTHY J. SOMMERER, DAVID J. SMITH, JASON TROTTER, STEVEN C. ACETO, *General Electric Research, Niskayuna, NY* A cold-cathode gas-discharge switch for the electric power grid must operate at the highest possible current density to be competitive. Magnetic enhancement, similar to that of a magnetron sputtering discharge, achieves current densities far above the classic "normal" cold-cathode fall current density. One of two physical mechanisms, power dissipation or sputtering, is likely to limit the ultimate current density of a magnetically enhanced device. Using forced cooling a power dissipation density of about 1 kW/cm^2 should be achievable. This corresponds to a current density of 5 A/cm^2 assuming a 200 V cathode fall. Sputtering can be much reduced using a light buffer gas such as hydrogen or helium. We are studying the transition to 'metal mode' operation in such discharges. Metal mode is often described as a current density at which lines of sputtered metal dominate buffer gas lines in the emission spectrum. Preliminary results in a magnetically enhanced discharge operating in the A/cm^2 range with helium buffer gas over some cathode materials are presented.

*The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

MW1 36 Operation of a high-voltage, high-power gaseous electronics switch for electric grid power conversion* TIMOTHY SOMMERER, SERGEY ZALUBOVSKY, *General Electric Research, Niskayuna, NY* A series of approximations and simple models is used to estimate the properties of a cold-cathode plasma in a high-voltage, high-power gas switch for use in grid-scale electric power conversion. The active volume is a plane-parallel gap $\sim$1 cm filled with hydrogen at a pressure $\sim$0.3 torr. A magnetic field in the region adjacent to the cathode is used to increase the current density to practical levels >1 A/cm^2. The estimated bulk plasma density is mid-10^{12} cm^{-3} and the electron temperature is $\sim$3 eV, to offset volume recombination. The magnetic field enhances ionization near the cathode and also impedes electron diffusion away from the region, sometimes resulting in a peak of plasma density in an extended presheath region. The switch is opened by applying a positive potential to a grid between the cathode and anode, leading to the formation of an ion matrix sheath around the grid, and an ion-acoustic wave that sweeps out the conducting plasma between the grid and the anode in about 1 μs.

*The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

MW1 37 Modeling of High-Power Gas Switch for Electric Grid System* ALEXANDER V. KHRABROV, JOHAN CARLSSON, IGOR D. KAGANOVICH, *Princeton Plasma Phys Lab* TIMOTHY SOMMERER, SERGEY ZALUBOVSKY, *GE Research* There has been recent interest in utilizing gas switches in high-power AC/DC conversion for the purpose of power transmission over long distances. These devices would be based on a glow discharge with magnetically insulated cold cathode [1]. Their operation is similar to sputtering magnetrons [2,3], but at much higher pressures (0.1 to 1 Torr) in order to achieve high current densities. We present results of numerical (the particle-in-cell code EDIPIC 1d3v PIC [4]) and analytical investigation of a gas switch in the conduction phase. The important properties of the high-pressure magnetron discharge are a very narrow cathode sheath and a considerable voltage drop in the magnetized pre-sheath where most of the ionization takes place due to Joule heating.

*The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

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[4]D. Sydorenko *et al.*, Phys. Rev. Lett. **103**, 145004 (2009).

MW1 38 Experimental and Numerical Investigation of the Dependency of Reaction Dynamics on the Plasma Gas Temperature in He/N_2 Cryoplasmas HITOSHI MUNEOKA, KEIICHIRO URABE, SVEN STAUSS, KAZUO TERASHIMA, *Department of Advanced Materials Science, The University of Tokyo* The plasma gas temperature (T_g) is one of the essential parameters in plasma science and technology, but so far, the effect of T_g on low-temperature high-gas-density plasma chemistry has not been investigated in detail yet. Cryoplasmas, which are defined as plasmas whose T_g can be controlled below room temperature (RT), have the potential for various applications. In this study, to investigate the effect of T_g on the reaction dynamics in He/N_2 cryoplasmas, we developed a new 0D reaction model and also investigated the cryoplasmas by time-resolved laser absorption spectroscopy (LAS) and optical emission spectroscopy (OES). LAS measurements in He cryoplasmas at the same gas density as at RT and 1 atm, showed a longer lifetime (>50 times) of metastable helium atom (He^m) at cryogenic temperature (CT) compared to those at RT. OES revealed a time delay of the N_2^+ emission peak relative to the He emission peak of a few microseconds, and the delay decreased with increasing T_g. The simulation using our reaction model suggested that the long lifetime of He^m at CT are due to the change of the reaction dynamics related to He^m as a function of T_g.

MW1 39 Electron avalanche and spark evolution along laser path in resonant laser-induced ignition STEVEN ADAMS, *Air Force Research Laboooratory, Wright-Patterson AFB* BOYD TOLSON, AMBER HENSLEY, *UES, Inc.* A multi-photon ionization scheme is studied that could provide laser-induced ignition within a high-voltage gap across an aircraft combustion chamber. The multi-photon resonant enhanced ionization (REMPI) technique could potentially be applied as a laser trigger from a compact low power laser source leading to breakdown and ignition of an aircraft air-fuel flow. In this experiment, an ultraviolet laser is passed through an aperture in the anode and into the flow chamber. The REMPI process forms an ionized channel between the electrodes and, with an applied electric field, eventually leads to breakdown precisely along the laser path. A delay time of 200 to 1000 ns between the laser pulse and breakdown event is typical for our range of conditions. High speed imaging and spectroscopic data reveal evidence of space charge regions and local field distortion within the inter-electrode space during the delay time and a model is applied to simulate the electron avalanche process. Spatially resolved spectroscopic analysis identifies various regions and degrees of laser photoionization, electron impact ionization, radical species and gas heating during the delay time.

MW1 40 Preliminary investigation of an atmospheric microplasma using Raman and Thomson laser scattering* BRADLEY SOMMERS, STEVEN ADAMS, *Air Force Research Laboratory, Wright-Patterson AFB* A triple grating spectrometer system has been coupled with an ultraviolet laser at 266 nm for the purpose of investigating Rayleigh, Raman, and Thomson scattering within atmospheric plasma sources. Such laser interactions present a non-invasive diagnostic to investigate small scale atmospheric plasma sources, which have recently garnered interest for applications in remote optical sensing, materials processing, and environmental decontamination. In this work, the laser scatter and temperature relationship were calibrated with a heated nitrogen cell held at atmospheric pressure while subsequent scattering measurements were made in atmospheric discharges composed of nitrogen and air. An adjustable electrode configuration and dc circuit were assembled to produce a microdischarge operating in normal glow mode, thus providing a non-thermal plasma in which the translational, rotational, vibrational and electron temperatures are not in equilibrium. Preliminary results include measurements of these temperatures, which were calculated by fitting simulated scattering spectra to the experimental data obtained using the triple grating spectrometer. Measured temperatures were also compared with those obtained using standard optical emission spectroscopy methods.

*Special thanks to the NRC Research Associateship Program.

MW1 41 Numerical Investigations of Positive Surface Streamer Discharges For High-Pressure Large Gap Arc Breakdown ASHISH SHARMA, LAXMINARAYAN RAJA, *Dept. of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin* Streamers are thin conducting channels which are formed by application of fast high-voltage pulses at the electrode surface. Surface streamers are used in a flash-lamp approach to initiate an arc breakdown in a large electrode gap at atmospheric and higher pressures. In this study, high-fidelity simulations are performed to study the propagation of cathode directed surface streamers into high pressure argon medium. The streamer model employed is based on the self-consistent multispecies and continuum description of the plasma. The model predicts transient dynamics of a surface streamer. Of particular interest is the conductivity of the streamer channel as a function of the electron density in the trail of the streamer head. The spatially continuous conductive streamer successfully bridges the gap between two electrodes from which an arc column can develop. The model predicts the conductivity of the streamer column as a function of gas properties, applied voltages on the electrodes and wall losses. The Model results compare favorably with accompanying experimental results for a flash-lamp based approach for large gap arc breakdown.

MW1 42 Atomic oxygen production scaling in a nanosecond-pulsed externally grounded dielectric barrier plasma jet BRIAN SANDS, *UES, Inc. (AFRL)* JACOB SCHMIDT, *Spectral Energies, LLC. (AFRL)* BISWA GANGULY, *UES, Inc. (AFRL)* JAMES SCOFIELD, *Air Force Research Laboratory* Atomic oxygen production is studied in a capillary dielectric barrier plasma jet that is externally grounded and driven with a 20-ns risetime positive unipolar pulsed voltage at pulse repetition rates up to 25 kHz. The power coupled to the discharge can be easily increased by increasing the pulse repetition rate. At a critical turnover frequency, determined by the net energy density coupled to the discharge, the plasma chemistry abruptly changes. This is indicated by increased plasma conductance and a transition in reactive oxygen species production from an ozone-dominated production regime below the turnover frequency to atomic-oxygen-dominated production at higher pulse rates. Here, we characterize atomic oxygen production scaling using spatially- and temporally-resolved two-photon absorption laser-induced-fluorescence (TALIF). Quantitative results are obtained via calibration with xenon using a similar laser excitation and collection system. These results are compared with quantitative ozone and discharge power measurements using a helium gas flow with oxygen admixtures up to 3%.

MW1 43 Characterization of combined power plasma jet using AC high voltage and nanosecond pulse for reactive species composition control KEISUKE TAKASHIMA, HIDEAKI KONISHI, TOSHIAKI KATO, TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University* In the application studies for both bio-medical and agricultural applications, the roles of the reactive oxide and/or nitride species generated in the plasma has been reported as a key to control the effects and ill-effects on the living organism. The correlation between total OH radical exposure from an air atmospheric pressure plasma jet and the sterilization threshold on Botrytis cinerea is presented. With the increase of the OH radical exposure to the Botrytis cinerea, the probability of sterilization is increased. In this study, to resolve the roles of reactive species including OH radicals, a combined power plasma jet using nanosecond pulses and low-frequency sinusoidal AC high voltage (a few kHz) is studied for controlling the composition of the reactive species. The nanosecond pulses are superimposed on the AC voltage which is in synchronization with the AC phase. The undergoing work to characterize the combined power discharge with electric charge and voltage cycle on the plasma jet will also be presented to discuss the discharge characteristics to control the composition of the reactive species.

MW1 44 Modeling of non-equilibrium and non-thermal plasma discharge in air: Three temperature modeling approach* RAJIB MAHAMUD, TANVIR FAROUK, *Department of Mechanical Engineering, University of South Carolina* The rapid progress in atmospheric pressure non-thermal plasma discharge has made air to be a preferable choice for feed gas. Despite the ease of operation of such discharges in air, the preference of air provides added complexity to modeling and simulations in terms of kinetics and different temperature modes. The diatomic nature of both N_2 and O_2 contributes to this complexity. In this work we report simulation results from a one-dimensional multi-physics model. A dc driven air plasma discharge operating at atmospheric and higher pressure is simulated. The model considers 50 species and 200 elementary reactions. The reaction scheme considers electron introduced and heavy particle reactions for N_2 and O_2 as well as interactions between nitrogen and oxygen. In addition to the species conservation equations, poisson's equation three different temperature's are resolved - electron, vibrational and translational. A special focus has been the coupling between the different temperatures to accurately resolve the energy cascade. The predictions from the model are found to be in good qualitative agreement against experimental measurements available in the literature.

*Work was supported by DARPA under Army Research Office (ARO) Grant No. W911NF1210007.

MW1 45 Comparison of Fabrication Techniques for Micro-Scale Spark Gap Plasma Switches* MATTHEW BURNETTE, DAVID STAACK, *None* Microplasma spark gaps with 2D geometries were fabricated by two techniques on alumina, first using photolithography and metal sputtering with thicknesses of hundreds of nanometers, and second using thermal-spray several microns thick, but with lower feature resolution. Several high temperature metals were tested as electrode material for the microplamsa device, including tungsten and chromium; however the chromium samples were not robust enough, eroding away too quickly for extensive testing. Scanning electron microscope (SEM) images were taken before and after testing to determine the wear on the samples. The sputtered tungsten thin films and thermal-spray deposited nickel films on alumina were compared after testing in 1 atm of helium running for one hour at a current of 1 mA. Slight wear and discoloration were noted on the anodes, yet significant erosion occurred on the cathodes; no wear was noted on the alumina. The thermally-sprayed nickel sample had the least wear, while the thin tungsten sample had the most wear. Discoloration was also seen on the nearby floating-voltage electrodes despite not being a part of the circuit, most likely due to heating. As the electrodes eroded, the plasma attachment point moved unpredictably.

*This work was supported in part by the Department of Defense Army Research Office under Grant W911NF1210007.

MW1 46 On cathode spot motion in magnetically driven high-pressure arcs* VALERIAN NEMCHINSKY, *Keiser University, Fort Lauderdale, Florida USA* VLADIMIR KOLOBOV, ROBERT ARSLANBEKOV, *CFD Research Corporation* High-pressure magnetically driven arcs are used in many industrial applications. In gas heaters, the arc is forced to rotate by axial magnetic fields along tubular electrodes to reduce electrode erosion. Many questions about the nature cathode and anode spot motion and electrode erosion remain unclear. We develop computational tool for simulations of electrode erosion in high pressure moving arcs. We assume that the operation of cathode spot operation in the high-pressure arc has many features of the vacuum arc (so called cold cathode mode) modified by the high pressure gas environment under high current density on the level of 10^9 A/m^2 and temperature exceeding melting point. The gas-dynamic interaction of the cathode vapor jet with background gas defines the erosion rate. We study the arc column attachment to the cathode. The arc column motion by the Lorentz force produces a tilt near the cathode due to time lag of electrode heating processes. It is suggested that the tilt of the arc column leads to asymmetry of the cathode voltage drop: it is larger at the leading end of the cathode attachment and lower at the opposite (trailing) end. The asymmetry of the cathode voltage drop causes asymmetry of the heat transfer to the cathode: it is shifted ahead of the cathode temperature distribution. As a result, the cathode spot moves catching up running away heat flux. The proposed model allows to connecting the tilt angle of the arc column with the speed of the arc rotation and current density at the cathode.

*Supported by an AFOSR STTR project monitored by Dr. M. Kendra.

MW1 47 Optical emission in a sonoplasma production system with the help of a punching metal plate K. SASAKI, Y. IWATA, S. TOMIOKA, S. NISHIYAMA, *Hokkaido University* N. TAKADA, *Nagoya University* Sonoplasmas are liquid-phase plasmas produced by ultrasonic power. We have reported an efficient method for producing standing sonoplasmas [1]. This method employs a punching metal plate which is inserted just below the water surface with the irradiation of ultrasonic wave. In this work, we examined spatiotemporal variations of optical emission (sonoluminescence) intensities from sonoplasmas. The optical emission images were captured at various phases using an ICCD camera. The region with the strong optical emission intensity coincided with the region with cavitation bubbles. In addition, the optical emission intensity was observed in the shrink phase of the sizes of cavitation bubbles. These experimental observations indicate that the optical emission is caused by sonoplasmas which are produced at the collapses of cavitation bubbles. Optical emissions were also observed at different positions and different phases, but the distributions of these optical emission intensities were broader than that observed at the shrink phase of cavitation bubbles. The distribution of the optical emission intensities can be utilized as a hint for understanding the spatiotemporal distribution of the ultrasonic power.

[1]Y. Iwata *et al.*, Appl. Phys. Express **6**, 127301 (2013).

MW1 48 Oxide nanoparticles synthesis via laser-induced plasma in liquid TAKU GOTO, HANSEL WEIHS, *Osaka University* MITSUHIRO HONDA, SERGEI KULINICH, *Tokai University* YOSHIKI SHIMIZU, *AIST* TSUYOHITO ITO, *Osaka University* Laser ablation in fluids has recently attracted a lot of attention as one of synthetic techniques to prepare new attractive nanomaterials, with the ability to control both product chemistry and morphology in many systems. In this study, we generated laser-induced plasma in H_2O – ethanol mixtures, while ablating metal targets to produce oxide nanoparticles and to study the effect of the medium on their properties. The ablated targets used in this study were Zn or Sn plates. A nanosecond Nd:YAG laser with the wavelength of 532 nm (10 Hz, 20–30 mJ/pulse) was applied to irradiate the targets. The liquid media were maintained at 0.1 to 30 MPa to study the effect of pressure. We found that the H_2O/ethanol ratio (at atmospheric pressure) can control the properties of the produced ZnO nanoparticles, such as defects and oxidation degree. The properties were examined by photoluminescence (PL) spectroscopy, X-ray diffraction, electron microscopies, and so on. More details will be presented at the symposium.

MW1 49 Comparison of temporal variation in emission intensity of OH(A) in after-glow period of Ar/H_2O and He/H_2O gas-mixture plasmas in water* TATSURU SHIRAFUJI, *Osaka City University* Previously, we have reported quite long duration (approx. 500 ns) of optical emission intensity of OH(A) in an after glow period of Ar plasma in water [1]. Numerical simulation has revealed that this phenomenon can be explained in terms of production of OH(A) through the reaction of H_3O^+ and low temperature electrons. We can perform similar plasma processing using He plasma in water with almost the same process performance in the case of decomposition of methylene blue molecules in aqueous solution. Thus, we have expected that the long duration of OH(A) optical emission can be observed also in He plasma in water. However, such long duration of OH(A) optical emission has not been observed in the case of He plasma in water. To understand this difference, we have performed numerical simulation of Ar/H_2O and He/H_2O plasmas, and discuss differences in major reaction pathways to produce OH(A) in Ar/H_2O and He/H_2O plasmas.

*This work has been partly supported by the Grant-in-Aid for Scientific Research on Priority Area "Frontier science of interactions between plasmas and nano-interfaces" from MEXT, Japan, and a Grant-in-Aid for Scientific Research (C) from JSPS.

[1]T. Shirafuji, Y. Oguda, and Y. Himeno, Jpn. J. Appl. Phys. **53**, 010211 (2014).

MW1 50 A two-phase multi-physics model for simulating plasma discharge in liquids ALI CHARCHI, TANVIR FAROUK, *Department of Mechanical Engineering, University of South Carolina* Plasma discharge in liquids has been a topic of interest in recent years both in terms of fundamental science as well as practical applications. Even though there has been a large amount of experimental work reported in the literature, modeling and simulation studies on plasma discharges in liquids is limited. To obtain a more detailed model for plasma discharge in liquid phase a two-phase multiphysics model has been developed. The model resolves both the liquid and gas phase and solves the mass and momentum conservation of the averaged species in both the phases. The fluid motion equation considers surface tension, electric field force as well as gravitational force. To calculate the electric force, the charge conservation equations for positive and negative ions and also for the electrons are solved. The Possion's equation is solved in each time step for obtaining a self consistent electric field. The obtained electric field and charge distribution is used to calculate the electric body force exerted on the fluid. Simulation show that the coupled effect of plasma, surface and gravity results in a time-evolving bubble shape. The influence of different plasma parameters on the bubble dynamics is studied.

MW1 51 Exploration of Underwater Laser Breakdown Using Two Synchronized Gated Cameras LUTZ HUWEL, CLAYTON BAUMGART, SUSANNAH BETTS, THOMAS J. MORGAN, *Wesleyan University* WILLIAM G. GRAHAM, *Queen's University Belfast* Using two synchronized intensified CCD cameras, we have studied spatial and temporal characteristics of optical breakdown in water created by a focused 10 ns pulsed Nd:YAG laser operating at 1064 nm. For three water samples with different impurity content (ultrapure, distilled, and tap water), the plasma evolution was monitored up to 1 ms after breakdown. Images taken by the two cameras, systematically delayed relative to each other, reveal that the center of emission intensity does not remain at a fixed location. In single plasma events, the center first moves, on average, toward the incoming laser beam. Then, at about 100 to 200 ns, the apparent direction of motion reverses and the center returns towards the focal point. On the other hand, in repetitive breakdown the time averaged center moves steadily downstream with each subsequent pulse. Details of this behavior depend on repetition frequency. We will also present shadowgraphy results revealing time resolved speeds of both shockwave and bubble expansion.

MW1 52 Modulation frequency dependence of bispectrum of laser light scattering intensity from nanoparticles formed in reactive plasmas* TEPPEI ITO, DAISUKE YAMASHITA, HYUNWOONG SEO, KUNIHIRO KAMATAKI, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* Interactions between plasmas and nano-interface are one of the most important issues in plasma processing. We have studied effects of plasma fluctuation on growth of nanoparticles in reactive dusty plasmas with amplitude modulation (AM) and have clarified that plasma fluctuation leads to generation of a large amount of nanoparticles with small size [1]. Here we report results of bispectrum analysis of time evolution of laser light scattering intensity from nanoparticles in reactive plasmas. Experiments were carried out using a capacitively-coupled discharge reactor. We employed Ar+DM-DMOS discharge plasmas to generate nanoparticles. We found higher harmonics and sub-harmonics in spectra of laser light scattering intensity, suggesting nonlinear coupling between plasma parameters and nanoparticle growth rate. We will report modulation frequency dependence of bispectrum of laser light scattering intensity.

*Work supported by MEXT.

[1]M. Shiratani *et al.*, Jpn. J. Appl. Phys. **53**, 010201 (2014).

MW1 53 Iodine as propellant for electric space propulsion PASCALINE GRONDEIN, PASCAL CHABERT, ANE AANESLAND, *Laboratoire de Physique des Plasmas* In PEGASES (an electric gridded thruster) both positive and negative ions are expelled after extraction from an ion-ion plasma formed downstream a localized magnetic field placed a few centimeters from the ionization region. For this thruster concept, we believe that Iodine is the best candidate. Its advantages are multiple: heavy and therefore good for high thrust, low ionization threshold and high electronegativity (the latter crucial for PEGASES) leading to high ion-ion densities and low RF power, at solid state at STP with a high vapor, and finally inexpensive. Iodine is also di-atomic and therefore energy loss in dissociation processes are reduced compared to SF6. We present here a dedicated experimental set-up intended for iodine experiments. The injection system consists of an evaporation chamber with temperature controlled gas lines and vacuum chamber to control condensation. A global model of the iodine electronegative plasma will be developed to compare and predict the plasma behavior and composition inside the thruster. The main challenge in this model is to reproduce the conditions of a strongly segregated plasma with two regions: one with rather high electron temperature and low electronegativity and the other an ion-ion plasma with low temperature.

MW1 54 Computational modeling of nanoparticle charging mechanism in a hydrocarbon flame PARTH SHAH, ALEXEI SAVELIEV, *North Carolina State University* A model that describes the charging mechanism of a 20 nm nanoparticle introduced in a methane-air counterflow laminar diffusion flame was developed and analyzed. The detailed kinetic model considers the production of ions and electrons in a methane-air flame due to chemi-ionization, thermal ionization and charging due to diffusion. The chemi-ionization model considers a one-step reaction that produces ions and electrons in a flame in addition to the detailed neutral reaction mechanism. The model is analyzed to study the effects of temperature, total nanoparticle concentration and chemi-ionization on charge formation in nanoparticles as well as on ions and electrons. The results show that thermal ionization is more dominant at high temperatures whereas diffusion charging is important at low temperatures. High concentration of nanoparticles influences the gas-phase ion and electron concentration to a very significant level whereas low concentration has a negligible effect on the same.

MW1 55 Negative ion surface production on carbon materials in hydrogen plasma: a thermodesorption analysis of carbon surface states GILLES CARTRY, KOSTIANTYN ACHKASOV, CÉDRIC PARDANAUD, JEAN-MARC LAYET, *PIIM, Aix Marseille University, CNRS* ALAIN SIMONIN, *IRFM, CEA Cadarache* ALIX GICQUEL, *LSPM, CNRS, Paris-Nord University* OTHMEN SAIDI, RÉGIS BISSON, THIERRY ANGOT, *PIIM, Aix Marseille University, CNRS* PIIM COLLABORATION, IRFM COLLABORATION, LSPM COLLABORATION Negative ion surface production in plasmas has been studied in the context of fusion where H-surface production in cesium-seeded plasmas is of a primary interest for neutral beam injection devices. Although surface production is much lower in Cs-free plasmas, it may be non-negligible. Indeed it has been observed that significant numbers of H-ions can be created on a graphite surface upon positive ion bombardment in H2 plasmas. Graphite material has been compared to a large variety of diamond layers, in particular poly-crystalline boron-doped and non-doped diamond thin films. It has been shown an enhancement of the negative-ion yield by a factor 5 for diamond materials at high temperature, while the yield continuously decreases for graphite. The difference is due to the different properties of the pristine materials but also to the modifications bring by the plasma to the materials during exposure. In order to study in detail these modifications, plasma exposed samples have been analyzed by Raman spectroscopy and Temperature Programmed Desorption (TPD). These diagnostics helped to trace the surface state changes of the materials and identify the reasons for the elevated negative ion production at high temperature on diamonds.

MW1 56 Mass- spectrometric Observations of Plasma-assisted Catalysis DAVE SEYMOUR, ALAN REES, DAVID LUNDIE, *Hiden Analytical* HIDEN TEAM Plasma discharges are known to facilitate the catalysis of reactive gas mixtures. A variety of plasmas, including surface barrier discharges, have been demonstrated to enhance the efficiency of the catalysts such as nickel/alumina or silver/alumina, used in conventional thermally–activated reactors. The observed improvements have included a lowering of the onset temperature at which the catalyst becomes effective, and an increase in the over-all efficiency of the process. A number of diagnostic methods have been employed to study the synergistic behaviour of plasmas and heated catalysts, the technique adopted often being specific to the monitoring of a particular reaction product. The work described here is aimed at demonstrating the versatility of mass-spectrometric methods in following the behaviour of typical plasma-assisted catalytic processes.

MW1 57 Structure and Characteristics of a Spherical Plasma Focus: Theory and Simulation YASAR AY, *North Carolina State University, Department of Nuclear Engineering, Raleigh, NC 27695, USA* MOHAMED A. ABDAL-HALIM, *Benha University, Faculty of Science, Department of Physics, 13518 Benha, Egypt* MOHAMED BOURHAM, *North Carolina State University, Department of Nuclear Engineering, Raleigh, NC 27695, USA* Most studies of dense plasma focus devices use cylindrical coaxial shapes, however, a spherical shape is investigated herein. Snow plow model and shock wave equations are coupled with the circuit equations to model the spherical plasma focus. Of interest in spherical plasma focus is to have both sheath expansion and the magnetic pressure changing rate for the rundown phase instead of the constant sheath only for the cylindrical case. The developed model is compared to published experimental results for validation and good agreement was obtained. Hydrogen and its isotopes were separately used for investigating the effect of the different molecular weights on plasma parameters. The gas pressure and discharge voltage were varied for these gases to study their effect on the plasma parameters. The study predicts a peak discharge current of 1.5 MA for tritium with 0.92 MA dip discharge current, and less for deuterium and hydrogen. The current drop for tritium indicates focus action. It indicates that the sheath velocity for heavy gases is lower than lighter gases. Predicted maximum temperature variation is about 11.1 eV for hydrogen, 14.6 eV for deuterium, 15.9 eV for DT mixture and 17eV for pure tritium; which indicates higher temperature with heavier gasses.

MW1 58 Feasibility Study of an EEDF Driven Rare Gas Metastable Laser* GUY PARSEY, *Michigan State University*

YAMAN GÜÇLÜ, *Max-Planck Institute* JOHN VERBONCOEUR, ANDREW CHRISTLIEB, *Michigan State University* Following advancements in dipole-pumped alkali vapor lasers (DPAL), it has been shown that metastable excited rare gas atoms exhibit similar spectral properties with an inherently less reactive gain medium. Rare gas lasers (RGL) use an electric discharge to maintain the metastable species densities analogous to heating for the alkali vapor, both of which focus on optical pumping to induce lasing with a three-level scheme. We propose using a modified electron energy distribution function (EEDF) to either modify RGL efficiency characteristics or to drive the optical gain process. Using our general-purpose kinetic global modeling framework (KGMf), we present a study on the effect of the EEDF on the RGL reaction kinetics with an emphasis on determining if lasing can be achieved without optical pumping. Considering the classical optically driven RGL as a baseline, we focus on the EEDF as a pumping mechanism. A pure Ar model is used along with models of Ar, Kr, Xe using He to drive collisional relaxation of the upper level.

*MSU Strategic Partnership Grant.

MW1 59 Characterization of Plasma Generated in a Commercial Grade Plasma Etching system GABRIELLA BESSINGER, DERETH DRAKE, *Valdosta State University* SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Old Dominion University* The use of plasma for etching and cleaning of many types of metal surfaces is becoming more prominent in industry. This is primarily due to the fact that plasma etching can reduce the amount of time necessary to clean/etch the surface and does not require large amounts of environmentally hazardous chemicals. Most plasma etching systems are designed and built in academic institutions. These systems provide reasonable etching rates and easy accessibility for monitoring plasma parameters. The downside is that the cost is typically high. Recently a number of commercial grade plasma etchers have been introduced on the market. These etching systems cost near a fraction of the price, making them a more economical choice for researchers in the field. However, very few academicians use these devices because their effectiveness has not yet been adequately verified in the current literature. We will present the results from experiments performed in a commercial grade plasma etching system, including analysis of the pulse characteristics observed by a photo diode and the plasma parameters obtained with optical emission spectroscopy.

MW1 60 Ion densities of CH_2F^+ and CHF_2^+ generated by dissociative ionization of charge exchange collisions in Ar or Kr diluted CH_2F_2 Plasmas MAKOTO SEKINE, YUSUKE KONDO, YUDAI MIYAWAKI, KENJI ISHIKAWA, TOSHIO HAYASHI, KEIGO TAKEDA, HIROKI KONDO, MASARU HORI, *Nagoya University* PLASMA NANOTECHNOLOGY TEAM Hydro-fluorocarbon gas, CH_xF_{4-x} is used for SiO_2 and Si_3N_4 etching, where the reduction of F in molecule leads high selectively. High selectively were reported as using hydro-fluorocarbon gases having more molecular mass such as C_5HF_7 [1]. H reacts to N and removes it from Si_3N_4. Therefore H works as an etchant of Si_3N_4. By using CH_2F_2 gas as an addition of conventional process, high selectively was obtained [2]. In order to understand the etch mechanism for the CH_2F_2 containing plasma, we investigate the gas phase species and reaction to produce etchants. In many cases, multiple fragmentation of the parent gas is suppressed by dilution of large amount of rare gas (M). Besides, dissociative ionization of charge exchange collisions, $CH_2F_2 + M^+ \rightarrow CH_2F^+ + F\cdot + M^*$ and $CHF_2^+ + H\cdot + M^*$ (M = Ar, Kr) has not been clarified yet. Here we show that the CH_2F^+ ion was dominant in the Ar-diluted plasma, because the channel of resonant dissociative ionization between Ar^+ (ca. 15.8 eV) and C-F bonding cleavage (ca. 15.6 eV) became dominant. In contrast, for the Kr-diluted plasma, similar exchange between Kr^+ (ca. 14.0 eV) and C-H bonding cleavage (ca. 13.9 eV) generated dominantly CHF_2^+ ion. This behavior in the fraction of ion densities in the CH_2F_2 plasma affects significantly to the selectivity.

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[2]M. Darnon *et al.*, J. Vac. Sci. & Tec. B **24**, 2262 (2006).

MW1 61 Roughness formation on photoresist during etching examined by HBr plasma-beam MAKOTO SEKINE, YAN ZHANG, KENJI ISHIKAWA, KEIGO TAKEDA, HIROKI KONDO, MASARU HORI, *Nagoya University* PLASMA NANOTECHNOLOGY TEAM For highly precise patterning in device fabrication, it is required to suppress roughness formations on photoresist (PR) polymers during plasma etching. HBr plasma treatment called "plasma cure" was proposed to reduce the roughness [1]. By using a beam irradiation, we reported the PR roughness formation in fluorocarbon plasma [2], and the effect of HBr cure. We report the roughness formation mechanism by surface analyses and power spectral density (PSD) of the roughness. Average slope and roll-off frequency of PSD are characterized by frequency components, the high-frequency roughness. We treated the data for six samples: a) pristine, b) after Ar plasma irradiation, c) after Ar plasma followed by HBr cure, d) after HBr cure, e) after HBr followed by Ar plasma beam, and f) after HBr followed by H_2 and Ar plasma beam irradiations. The PSD slopes were changed by each process. Based on the results, we speculated that the Ar-plasma beam formed a crust layer on the PR surface with unrelieved stress and HBr cure may soften the bulk PR to relieve the stress and cause agglomeration of polymers at the size over 10 nm.

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[2]T. Takeuchi *et al.*, J. Phys. D: Appl. Phys. **46**, 102001 (2013).

MW1 62 N-doped TiO_2 Prepared by RF DBD Plasma ZHI-GUANG SUN, JING-LIN LIU, XIAO-SONG LI, ZHAO-JUN ZHAI, AI-MIN ZHU, *Dalian University of Technology* LABORATORY OF PLASMA PHYSICAL CHEMISTRY TEAM TiO_2 is the most promising photocatalyst because of its chemical stable, nontoxic, low cost, high photocatalytic activity and other attractive properties. Anatase has the highest photocatalytic activity among the three crystal form of TiO_2. However, the 3.2 eV bandgap of anatase TiO_2 makes it can only utilize the ultraviolet part of solar spectrum. Nitrogen doping is an effective method to extend the absorption range of anatase to visible light. N-doped TiO_2 preparation methods, such as heat treatment under NH_3 flow, the hydrolytic precipitation and the sol-gel process, have been reported. In this work, preparation of N-doped TiO_2 was explored by radio-frequency (RF) dielectric barrier discharge (DBD) plasma using Ar as discharge gas. $TiCl_4$, O_2 and N_2 were used as Ti, O and N precursors, respectively. In addition, H_2 was added to the plasma. X-ray photoelectron spectra (XPS) showed nitrogen was successfully doped into the as-prepared TiO_2. Further investigations on structure, composition and optical property of the as-prepared TiO_2 samples were conducted by X-ray diffraction (XRD), Fourier-transform infrared (FT-IR) and UV-Vis absorption spectra techniques.

MW1 63 Cluster Incorporation Control by Hydrogen Silane Mixture in Multi Hollow Discharge Plasma CVD* SUSUMU

TOKO, YOSHIHIRO TORIGOE, YOSHINORI KANEMITU, HUNWOONG SEO, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* Light-induced degradation has been one of the most important issues for hydrogenated amorphous silicon (a-Si:H) solar cells. In SiH4 discharges employed for a-Si:H deposition, there coexist SiH3 radicals and clusters. Our previous results show that incorporation of amorphous silicon clusters is responsible for the light-induced degradation. Therefore, it is important to control the incorporation of clusters into films. We have developed multi-hollow discharge plasma CVD method, by which clusters are driven toward the downstream region and high quality a-Si:H films can be deposited in the upstream region. In this study, we report that the generation rate of clusters and the amount of clusters incorporated into films can be controlled by hydrogen silane mixture. The generation rate of clusters correlates with electron temperature, which information was obtained by the optical emission intensity ratio $ISi^*/ISiH^*$. The amount of cluster incorporation was measured with quartz crystal microbalances (QCMs) [1]. With decreasing hydrogen gas flow rate the amount of cluster incorporation decreases.

*Work supported by NEDO and PVTEC.

[1]Y. Kim *et al.*, Jpn. J. Appl. Phys. **52**, 01AD01 (2013).

MW1 64 Effect of oxygen atoms dissociated by non-equilibrium plasma on flame of methane oxygen and argon pre-mixture gas* HARUAKI AKASHI, TOMOKAZU YOSHINAGA, *National Defense Academy* KOICHI SASAKI, *Hokkaido Univ.* For more efficient way of combustion, plasma-assisted combustion has been investigated by many researchers. But it is very difficult to clarify the effect of plasma even on the flame of methane. Because there are many complex chemical reactions in combustion system. Sasaki *et al.* [1] has reported that the flame length of methane and air premixed burner shortened by irradiating microwave power. They also measured emission from Second Positive Band System of nitrogen during the irradiation. The emission indicates existence of high energy electrons which are accelerated by the microwave. The high energy electrons also dissociate oxygen molecules easily and oxygen atom would have some effects on the flame. But the dissociation ratio of oxygen molecules by the non-equilibrium plasma is significantly low, compared to that in the combustion reaction. To clarify the effect of dissociated oxygen atoms on the flame, dependence of dissociation ratio of oxygen on the flame has been examined using CHEMKIN. It is found that in the case of low dissociation ratio of 10^{-6}, the ignition of the flame becomes slightly earlier. It is also found that in the case of high dissociation ratio of 10^{-3}, the ignition time becomes significantly earlier by almost half.

*This work was supported by KAKENHI (22340170).

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MW1 65 Multiplex coherent anti-Stokes Raman scattering microspectroscopy for monitoring molecular structural change in biological samples TAKAYUKI OHTA, *Meijo University* HIROSHI HASHIZUME, KEIGO TAKEDA, KENJI ISHIKAWA, *Nagoya University* MASAFUMI ITO, *Meijo University* MASARU HORI, *Nagoya University* Biological applications employing non-equilibrium plasma processing has been attracted much attention. It is essential to monitor the changes in an intracellular structure of the cell during the plasma exposure. In this study, we have analyzed the molecular structure of biological samples using multiplex coherent anti-Stokes Raman scattering (CARS) microspectroscopy. Two picosecond pulse lasers with fundamental (1064 nm) or the supercontinuum (460-2200 nm) were employed as a pump and Stokes beams of multiplex CARS microspectroscopy, respectively. The pump and the Stokes laser beams were collinearly overlapped and tightly focused into a sample using an objective lens of high numerical aperture. The CARS signal was collected by another microscope objective lens which is placed facing the first one. After passing through a short pass filter, the signal was dispersed by a polychromator, and was detected by a charge-coupled device camera. The sample was sandwiched by a coverslip and a glass bottom dish for the measurements and was placed on a piezo stage. The CARS signals of the quinhydrone crystal at 1655, 1584, 1237 and 1161 cm^{-1} were assigned to the C-C, C=O stretching, O-H and C-O stretching vibrational modes, respectively.

MW1 66 Inactivation of the biofilm by the air plasma containing water RYOTA SUGANUMA, KOICHI YASUOKA, *Tokyo Inst of Tech - Tokyo* YASUOKA TAKEUCHI LAB TEAM Biofilms are caused by environmental degradation in food factory and medical facilities. Inactivation of biofilm has the method of making it react to chemicals including chlorine, hydrogen peroxide, and ozone. Although inactivation by chemicals has the problem that hazardous property of a residual substance and hydrogen peroxide have slow reaction velocity. We achieved advanced oxidation process (AOP) with air plasma. Hydrogen peroxide and ozone, which were used for the formation of OH radicals in our experiment, were able to be generated selectively by adjusting the amount of water supplied to the plasma. We inactivated Pseudomonas aeruginosa biofilm in five minutes with OH radicals generated by using hydrogen peroxide and ozone.

MW1 67 VUV-Photoionization CES-Detector of Volatile Bio-Marker Molecules ALEXANDER MUSTAFAEV, *National Mineral Resources University, St.-Petersburg, Russia* NATALIYA LUNEVA, *St.-Petersburg State University, Faculty of Dentistry and Medical Technologies, Russia* GEORGE PANASYUK, *UES Inc., Dayton OH 45432, USA* NIKOLAY TIMOFEEV, *St.-Petersburg State University, Faculty of Physics, Russia* ALEXANDER TSYGANOV, *Spectrum-Micro LLC, St.-Petersburg, 191036 Russia* Energy spectra of characteristic electrons released via photoionization by vacuum ultraviolet (VUV) radiation of admixture molecules in the atmospheric air, not using traditional evacuated energy analyzers, can be determined by Collisional Electron Spectroscopy (CES) method [1]. Some details of CES-photoionization sensor were described in [2]. Our further developments are devoted to application of CES-detectors for a mobile continuous biochemical diagnostics. It is known that "on breathing" it is possible to find out volatile bio-marker molecules of a lot of diseases (lung cancer, tuberculosis, COPD, asthma, diabetes, kidney disease, mammary cancer, Crohn's disease, ulcerative colitis, etc). But today's weighty and expensive laboratory equipment (like GC MS) provides observation of these bio-markers only during patients' visits to a doctor. In this way we study pocket-size CES-sensor with micro-plasma krypton resonance radiation source (10.6 eV photons) for the photoionization detection of metabolic ammonia, ethanol, acetone and pentane molecules directly in atmospheric air.

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[2]G. Y. Panasyuk and A. B. Tsyganov, J. Appl. Phys. **111**, 114503 (2012).

MW1 68 Single and multiple streamer DBD micro-discharges for testing inactivation of biologically contaminated surfaces* VACLAV PRUKNER, EVA DOLEZALOVA, MILAN SIMEK, *Institute of Plasma Physics AS CR, v.v.i., Department of Pulse*

Plasma Systems, Za Slovankou 3, 18200 Prague, Czech Republic Highly reactive environment produced by atmospheric-pressure, non-equilibrium plasmas generated by surface dielectric barrier discharges (SDBDs) may be used for inactivation of biologically contaminated surfaces. We investigated decontamination efficiency of reactive environment produced by single/multiple surface streamer micro-discharge driven by amplitude-modulated AC power in coplanar electrode geometry on biologically contaminated surface by *Escherichia coli*. The discharges were fed by synthetic air with water vapor admixtures at atmospheric pressure, time of treatment was set from 10 second to 10 minutes, diameters of used SDBD electrodes (single and multiple streamer) and homogeneously contaminated disc samples were equal (25 mm), the distance between the electrode and contaminated surface was 2 mm. Both a conventional cultivation and fluorescent method LIVE/DEAD Bacterial Viability kit were applied to estimate counts of bacteria after the plasma treatment. Inactivation was effective and bacteria partly lost ability to grow and became injured and viable/active but non-cultivable (VBNC/ABNC).

*Work was supported by the MEYS under Project LD13010, VES13 COST CZ (COST Action MP 1101).

MW1 69 Diagnostics of AC excited Atmospheric Pressure Plasma Jet with He for Biomedical Applications MASARU HORI, KEIGO TAKEDA, TAKUMI KUMAKURA, KENJI ISHIKAWA, HIROMASA TANAKA, HIROKI KONDO, MAKOTO SEKINE, *Nagoya University* YOSHIHIRO NAKAI, *NU Global* Atmospheric pressure plasma jets (APPJ) are frequently used for biomedical applications. Reactive species generated by the APPJ play important roles for treatments of biomedical samples. Therefore, high density APPJ sources are required to realize the high performance. Our group has developed AC excited Ar APPJ with electron density as high as 10^{15} cm^{-3}, and realized the selective killing of cancer cells and the inactivate spores of *Penicillium digitatum*. Recently, a new spot-size AC excited APPJ with He gas have been developed. In this study, the He APPJ was characterized by using spectroscopy. The plasma was discharged at a He flow rate of 5 slm and a discharge voltage of AC 9 kV. Gas temperature and electron density of the APPJ were measured by optical emission spectroscopy. From theoretical fitting of 2nd positive system of N_2 emission (380.4 nm) and Stark broadening of Balmer β line of H atom (486.1 nm), the gas temperature and the electron density was estimated to be 299 K and 3.4. $\times$ 10^{15} cm^{-3}. The AC excited He APPJ has a potential to realize high density with room temperature and become a very powerful tool for biomedical applications.

MW1 70 Comparison of plasma generated nitrogen fertilizer to conventional fertilizers ammonium nitrate and sodium nitrate for pre-emergent and seedling growth A. ANDHAVARAPU, W. KING, A. LINDSAY, B. BYRNS, D. KNAPPE, W. FONTENO, S. SHANNON, *North Carolina State University* Plasma source generated nitrogen fertilizer is compared to conventional nitrogen fertilizers in water for plant growth. Root, shoot sizes, and weights are used to examine differences between plant treatment groups. With a simple coaxial structure creating a large-volume atmospheric glow discharge, a 162 MHz generator drives the air plasma. The VHF plasma source emits a steady state glow; the high drive frequency is believed to inhibit the glow-to-arc transition for non-thermal discharge generation. To create the plasma activated water (PAW) solutions used for plant treatment, the discharge is held over distilled water until a 100 ppm nitrate aqueous concentration is achieved. The discharge is used to incorporate nitrogen species into aqueous solution, which is used to fertilize radishes, marigolds, and tomatoes. In a four week experiment, these plants are watered with four different solutions: tap water, dissolved ammonium nitrate DI water, dissolved sodium nitrate DI water, and PAW. Ammonium nitrate solution has the same amount of total nitrogen as PAW; sodium nitrate solution has the same amount of nitrate as PAW. T-tests are used to determine statistical significance in plant group growth differences. PAW fertilization chemical mechanisms are presented.

MW1 71 Numerical Simulation of Acceleration and Deceleration of Weakly-Ionized Rarefied Arc-Jet along Diverging Magnetic Field HIROSHI AKATSUKA, SATOSHI TSUNO, AMPAN LAOSUNTHARA, ATSUSHI NEZU, HARUAKI MATSUURA, *Tokyo Institute of Technology* We are studying supersonic helium plasma jet along a diverging magnetic field with low-ionization degree and low electron density. It had been experimentally found that the ion Mach number had its maximum about 3 at 1 cm downstream after passing the magnetic nozzle, and after that, the ion Mach number turned to decrease, and the plasma potential dropped. We numerically simulated the expanding plasma along the open magnetic field. Considering dimensionless numbers of the plasma flow, we chose hybrid scheme, i.e., Direct Simulation Monte Carlo (DSMC) method for neutral particles and ions, and fluid method for electrons. Residual molecules in the vacuum chamber were also included as particles. Consequently, we find the velocity increase just after passing the open field line, followed by deceleration due to collisions with residual molecules with temperature increase. In this acceleration-deceleration phenomenon, the velocity difference between neutrals and charged species are found, which also affects the space potential. We discuss the mechanisms of potential formation by the pressure difference and the friction force between the charged particles and neutral species. The numerical results are, at least qualitatively, consistent with our previous experimental results.

MW1 72 Dependence of an ion current on a working voltage for Hall thruster TAL-WSF/D-55. Simple theory and experiment NIKOLAY SHUMILIN, *Moscow Institute of Electronics and Mathematics National Research University Higher School of Economics* VLADIMIR SHUMILIN, *All-Russia Electrotechnical Institute* ALEXANDER SHUMILIN, *Moscow Institute of Electronics and Mathematics National Research University Higher School of Economics* In paper [1] the simple model for the definition of interrelation between integral characteristics of Hall thrusters with an anode layer is offered. Concrete calculations were made for one of most often used Hall thrusters - TAL-WSF/D-55. While analysing the received theoretical dependences an attempt of comparison with results of an experimental research of thruster TAL-WSF/D-55 was made. With this purpose experimental dependence of specific impulse of Hall thruster TAL-WSF/D-55 on working voltage in range from 150 up to 350 V resulted in [2] was used. It appeared, that these data contain some serious mistake and there is no reference to original works in this paper. In present report this mistake is corrected using original works [3]. It is shown, that the offered simple model gives results close to a reality both qualitatively and quantitatively.

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MW1 73 Kinetic Modeling of Martian Atmosphere Aerobraking Plasma DERETH DRAKE, EVAN SMITHWICK, *Valdosta State University* During Martian atmospheric aerobraking the plasma that forms around a spacecraft can be considered a high-volume plasma reactor that is sustained by the dissipation of the spacecraft's kinetic energy. At altitudes below 100 km, it has been shown that the plasma parameters vary considerably depending on the spacecraft's trajectory. However, in the range which is applicable to aerobraking, 100 km $< h <$ 200 km, little of this work has been completed. We have evaluated a simple kinetic model to determine a probable range of plasma parameters for altitudes between 100 and 200 km using existing Martian atmospheric data and available probe trajectories.

MW1 74 Study of Unsteady Flow Actuation Produced by Surface Plasma Actuator on 2-D Airfoil MINH KHANG PHAN, JICHUL SHIN, *University of Ulsan* Effect of flow actuation driven by low current continuous or pulsed DC surface glow discharge plasma actuator is studied. Schlieren image of induced flow on flat plate taken at a high repetition rate reveals that the actuation is mostly initiated near the cathode. Assuming that the actuation is mostly achieved by ions in the cathode sheath region, numerical model for the source of flow actuation is obtained by analytical estimation of ion pressure force created in DC plasma sheath near the cathode and added in momentum equation as a body force term. Modeled plasma flow actuator is simulated with NACA0012 airfoil oscillating over a certain range of angle of attack (AoA) at specific reduced frequencies of airfoil. By changing actuation authority according to the change in AoA, stabilization of unsteady flow field is improved and hence steady aerodynamic performance can be maintained. Computational result shows that plasma actuation is only effective in modifying aerodynamic characteristics of separated flow. It turns out that plasma pulse frequency should be tuned for optimal performance depending on phase angle and rotating speed. The actuation authority can be parameterized by a ratio between plasma pulse frequency and reduced frequency.

MW1 75 Self-assembled Ag nano-patterns forming in downflow of ammonia-Ar atmospheric pressure microplasmas NAOYA KIHARA, ELLA BLANQUET, OSAMU SAKAI, *Kyoto University* Fractal-like Ag nano-patterns were observed after drying silver nitrate solution in downflow of ammonia-Ar atmospheric pressure microplasmas. These atmospheric-pressure microplasmas generated hydrazine, and this hydrazine density in their downflow region was in the order of 10^{15} cm^{-3} [1]. As hydrazine is a very strong reducing agent, Ag nano-particles were extracted from the silver nitrate solution. The Ag nano-structures were fractal-like patterns, with fractal dimension range of 1.6–1.9. The network structures in these patterns with several mm diameter showed good electric conductivity and extraordinary optical responses, which will be favorable for future low-cost optical metamaterials.

[1]K. Urabe, Y. Hiraoka, and O. Sakai, Plasma Sources Sci. Technol. **22**, 032003 (2013).

MW1 76 Interactions between plasma-treated carbon nanotubes and electrically neutral materials DAISUKE OGAWA, KEIJI NAKAMURA, *Chubu University* A plasma treatment can create dangling bonds on the surface of carbon nanotubes (CNTs). The dangling bonds are so reactive that the bonds possibly interact with other neutral species even out of the plasma if the lifetime of the bonds is effectively long. In order to have good understandings with the interactions, we placed multi-wall CNTs (MWCNTs) in atmospheric dielectric barrier discharge that was created in a closed environment with the voltage at 5 kV. We set 50 W for the operating power and 15 minutes for the process time for this plasma treatment. Our preliminary results showed that the reaction between dangling bonds and neutrals likely occurred in the situation when CNTs were treated with argon plasma, and then exposed in a nitrogen-rich dry box. We did Fourier transform infrared (FTIR) spectroscopy after the treatments. The measurement showed that the spectrum with plasma-treated CNTs was different from pristine CNTs. This is an indication that the plasma-treated CNTs have reactive cites on the surface even after the discharge ($\sim$ minutes), and then the CNTs likely reacted with the neutral species that causes the different spectrum. In this poster, we will show more details from our results and further progresses from this research.

MW1 77 Optimizing Natural Gas Networks through Dynamic Manifold Theory and a Decentralized Algorithm: Belgium Case Study CALEB KOCH, LEIGH WINFREY, *Virginia Tech* Natural Gas is a major energy source in Europe, yet political instabilities have the potential to disrupt access and supply. Energy resilience is an increasingly essential construct and begins with transmission network design. This study proposes a new way of thinking about modelling natural gas flow. Rather than relying on classical economic models, this problem is cast into a time-dependent Hamiltonian dynamics discussion. Traditional Natural Gas constraints, including inelastic demand and maximum/minimum pipe flows, are portrayed as energy functions and built into the dynamics of each pipe flow. Doing so allows the constraints to be built into the dynamics of each pipeline. As time progresses in the model, natural gas flow rates find the minimum energy, thus the optimal gas flow rates. The most important result of this study is using dynamical principles to ensure the output of natural gas at demand nodes remains constant, which is important for country to country natural gas transmission. Another important step in this study is building the dynamics of each flow in a decentralized algorithm format. Decentralized regulation has solved congestion problems for internet data flow, traffic flow, epidemiology, and as demonstrated in this study can solve the problem of Natural Gas congestion. A mathematical description is provided for how decentralized regulation leads to globally optimized network flow. Furthermore, the dynamical principles and decentralized algorithm are applied to a case study of the Fluxys Belgium Natural Gas Network.

MW1 78 Plasma Modeling of Electrosurgery SCOTT JENSEN, DANIEL FRIEDRICHS, JAMES GILBERT, WOUNJHANG PARK, DRAGAN MAKSIMOVIC, *University of Colorado-Boulder* Electrosurgery is the use of high frequency alternating current (AC) to illicit a clinical response in tissue, such as cutting or cauterization. Power electronics converters have been demonstrated to generate the necessary output voltage and current for electrosurgery. The design goal of the converter is to regulate output power while supplying high frequency AC. The design is complicated by fast current and voltage transients that occur when the current travels through air in the form of an arc. To assist in designing a converter that maintains the desired output power during these transients, we have used the COMSOL Plasma Module to determine the output voltage and current characteristics during an arc. This plasma model, used in conjunction with linear circuit elements, allows the full electrosurgical system to be validated. Two models have been tested with the COMSOL Plasma Module. One is a four-species, four-reaction model based on the local field approximation technique. The second simulates the underlying air chemistry using 30 species, 151 chemical reactions, and a coupled electron energy distribution function. Experimental output voltage and current samples have been collected and compared to both models.

MW1 79 POSTDEADLINE

MW1 80 Solutions of the low-frequency plasma sheath circuit equations MIRKO VUKOVIC, *Tokyo Electron, US Holdings, Inc.* We derive a relation between the time derivatives of the current and voltage of the low-frequency plasma sheath. This relation is used to derive a first order differential equation for the electrical current in a driven series resistor, capacitor, and sheath circuit. Analytic and semi-numeric solutions are obtained for pulse and periodic excitations. We use these solutions to analyze the Langmuir probe response in some common diagnostic applications: the pulse excitation [1] and AC Bias [2] methods.

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[2]Van Nieuwenhove and Van Oost, Rev. Sci. Instrum. **59**(7), July (1988).

MW1 81 Atomic Layer Etching of Silicon to Solve ARDE-Selectivity-Profile-Uniformity Trade-Offs MINGMEI WANG, ALOK RANJAN, *TEL Technology Center, America, LLC* PETER VENTZEK, *Tokyo Electron America, Inc.* AKIRA KOSHIISHI, *Tokyo Electron Miyagi Ltd.* With shrinking critical dimensions, dry etch faces more and more challenges. Minimizing each of aspect ratio dependent etching (ARDE), bowing, undercut, selectivity, and within die uniformly across a wafer are met by trading off one requirement against another. At the root of the problem is that roles radical flux, ion flux and ion energy play may be both good and bad. Increasing one parameter helps meeting one requirement but hinders meeting the other. Self-limiting processes like atomic layer etching (ALE) promise a way to escape the problem of balancing trade-offs. ALE [1] was realized in the mid-1990s but the industrial implementation has been slow. In recent years interest in ALE has revived. We present how ARDE, bowing/selectivity trade-offs may be overcome by varying radical/ion ratio, byproduct re-deposition. We overcome many of the practical implementation issues associated with ALE by precise passivation process control. The Monte Carlo Feature Profile Model (MCFPM) is used to illustrate realistic scenarios built around an Ar/Cl_2 chemistry driven etch of Si masked by SiO_2. We demonstrate that ALE can achieve zero ARDE and infinite selectivity. Profile control depends on careful management of the ion energies and angles. For ALE to be realized in production environment, tight control of IAD is a necessary. Experimental results are compared with simulation results to provide context to the work [1].

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MW1 82 Interfacial instability of wormlike micellar solutions sheared in a Taylor-Couette cell HADI MOHAMMADIGOUSHKI, SUSAN J. MULLER, *Chemical and Biomolecular Engineering-UC Berkeley* We report experiments on wormlike micellar solutions sheared in a custom-made Taylor-Couette (TC) cell. The computer controlled TC cell allows us to rotate both cylinders independently. Wormlike micellar solutions containing water, CTAB, and NaNo3 with different compositions are highly elastic and exhibit shear banding within a range of shear rate. We visualized the flow field in the θ-z as well as r-z planes, using multiple cameras. When subject to low shear rates, the flow is stable and azimuthal, but becomes unstable above a certain threshold shear rate. This shear rate coincides with the onset of shear banding. Visualizing the θ-z plane shows that this instability is characterized by stationary bands equally spaced in the z direction. Increasing the shear rate results to larger wave lengths. Above a critical shear rate, experiments reveal a chaotic behavior reminiscent of elastic turbulence. We also studied the effect of ramp speed on the onset of instability and report an acceleration below which the critical Weissenberg number for onset of instability is unaffected. Moreover, visualizations in the r-z direction reveals that the interface between the two bands undulates. The shear band evolves towards the outer cylinder upon increasing the shear rate, regardless of which cylinder is rotating.

MW1 83 Inelastic processes of electron interactions with halouracils – cancer therapy agents CHETAN LIMBACHIYA, *The M.S. University of Baroda, Vadodara, India* MINAXI VINODKUMAR, *V.P. Science College, Vallabh Vidyanagar, India* MOHIT SWADIA, *P.S. Science College, Kadi, India* We report electron impact total inelastic cross sections for important cancer treatment agents, 5-fluorouracil (5FU), 5-chlorouracil (5ClU) and 5-bromouracil (5BrU) from ionization threshold through 5000 eV. We have employed Spherical Complex Optical Potential [1,2] method to compute total inelastic cross sections Q_{inel} and Complex Scattering Potential – ionization contribution (CSP-ic) formalism, to calculate total ionization cross sections Q_{ion}. Electron driven ionization cross sections for these important compounds of therapeutic interest are reported for the first time in this work. In absence of any ionization study for these cancer therapy agents, we have compared the data with their parent molecule Uracil. Present cross sections may serve as a reference estimates for experimental work.

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[2]Chetan Limbachiya *et al.*, Mol. Phys. **112**(1), 101 (2014)

MW1 84 Study of striations in a spherically symmetric hydrogen discharge LOWELL MORGAN, *Kinema Research & Software, LLC* MONTY CHILDS, MICHAEL CLARAGE, PAUL ANDERSON, *Aurtas International, Inc.* We have observed, in experiments similar to those of [1,2], multiple spherically symmetric striations or double-layers in a hydrogen discharge, sometimes containing a small amount of helium having a total gas pressure in the range 0.7–5 Torr. The discharge is a positive corona around a 6mm diameter steel anode driven by a 600 V, max 3 Amp DC power supply. Using mass spectrometry we have found that sometimes as much as 10% of the H_2 is dissociated into atomic hydrogen. The dominant positive ion is H_3^+. We have performed UV, visible, and near-IR spectroscopy of the plasma looking at line ratios and Stark broadening in order to obtain an estimate of electron temperature and density. We have also performed Abel transforms on images of the striations in order to find the true relative broad band emissivity from the optically thin plasma as a function of radius out from the anode finding that, typically, it peaks several anode radii out into the plasma striations. Some modeling and simulation of the plasma chemistry and transport will also be presented. Research supported by the International Science Foundation.

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MW1 85 Investigation of the rates of surface and bulk ROS-generating reactions using indigo dye as an indicator CARLY ANDERSON, DOUGLAS CLARK, DAVID GRAVES, *University of California, Berkeley* We present evidence for the existence of two distinct processes that contribute to the generation of reactive oxygen and nitrogen species (RONS) in liquids exposed to cold atmospheric plasma (CAP) in air. At the plasma-liquid interface, there exists a fast surface reaction zone where RONS from the gas phase interact with species in the liquid. RONS can also be produced by "slow" chemical reactions in the bulk liquid, even long after plasma exposure. To separate the effects of these processes, we used indigo dye as an indicator of ROS production; specifically generation of hydroxyl radical. The rate of indigo decolorization while in direct contact with CAP is compared with the expected rate of hydroxyl radical generation at the liquid surface. When added to aqueous solutions after CAP exposure, indigo dye reacts on a time scale consistent with the production of peroxynitrous acid, ONOOH, which is known to decompose to hydroxyl radical below a pH of 6.8. In this study, the CAP used was a air corona discharge plasma run in a positive streamer mode.

MW1 86 A Global Enhanced Vibrational Kinetic Model for Investigation of Negative Hydrogen Ion Sources SERGEY AVERKIN, NIKOLAOS GATSONIS, *Worcester Polytechnic Institute* A new Global Enhanced Vibrational Kinetic Model (GEVKM) is developed for modeling negative hydrogen ion production and destruction processes in low (mTorr level) to high pressure (Torr level) ion sources. GEVKM couples steady-state space averaged continuity equations for ground-state neutral H_2, H species, 14 vibrationally excited molecular hydrogen species $H_2(v)$, positive ions H^+,H_2^+,H_3^+,negative ions H^-, electronically excited hydrogen atoms $H(n = 2\text{–}3)$, and electrons with electron energy and total energy equations. Compared to previous global models GEVKM includes a full vibrational kinetics treatment, a self-consistent evaluation of heavy particle temperature and spatial variation of species densities in estimation of wall fluxes. The input parameters to GEVKM are ion source geometry, inlet hydrogen flow rate and absorbed power and outputs include concentration and temperature of all species. The GEVKM is verified and validated by comparisons with previous experimental and computational results for a low pressure (10–100 mTorr) volume negative ion source and a high pressure (10–100 Torr) microwave generated hydrogen plasma reactor. The GEVKM is also used for a parametric investigation of a new high pressure negative hydrogen ion source that includes the RF discharge chamber and a nozzle.

MW1 87 Electron density and temperature diagnostics for atmospheric pressure plasmas using continuum radiation SANGHOO PARK, *Korea Advanced Institute of Science and Technology* SE YOUN MOON, *Chonbuk National University* WONHO CHOE, *Korea Advanced Institute of Science and Technology* Information on electrons is particularly valuable because most of the important plasma reactions are governed by electron kinetics. However, diagnostics of electron density (n_e) and temperature (T_e) of low temperature atmospheric pressure plasmas is still challenging although there are some advanced diagnostics available such as laser Thomson scattering or optical emission spectroscopy combined with complex plasma equilibrium models. In this work, we report a simple spectroscopic diagnostic method with high temporal and spatial resolution based on continuum radiation in the UV and visible range for n_e and T_e. Together with the basic principle for the diagnostics including electron-atom bremsstrahlung (or neutral bremsstrahlung) and hydrogen radiative dissociation continuum, some experimental results in several argon and helium atmospheric pressure plasmas will be presented. In a typical argon 13.56 MHz parallel plate capacitive discharge, the measured values are T_e = 2.5 eV and $n_e = 0.7\text{–}1.1 \times 10^{12}$ cm^{-3} at P_{rf} = 110–200 W. Two-dimensional T_e profile of an Ar pulsed plasma jet using a DSLR camera and this diagnostics will also be shown.

MW1 88 High-energy tail formation in an ion energy distribution function in the cylindrical Hall thruster plasma YOUBONG LIM, HOLAK KIM, JAESUN PARK, *Korea Advanced Institute of Science and Technology* JONGHO SEON, *Kyung Hee University* WONHO CHOE, *Korea Advanced Institute of Science and Technology* Ion energy distribution functions (IEDFs) of individual ion species having different charge states (i.e. Xe^+, Xe^{2+}, Xe^{3+}, etc.) in the Hall thruster plasma are obtained from the measured E × B probe spectrum by a novel inversion technique using the iterative Tikhonov regularization method. The obtained IEDFs show the existence of a high-energy tail in the cylindrical Hall thruster plasmas that is mainly due to Xe^+ ions despite the presence of Xe^{2+} and Xe^{3+} ions with a large fraction. Ion dynamics inside the plasma was numerically investigated to demonstrate that the high-energy tail is due to nonlinear ion acceleration in the plasma oscillating at typically 100 to 500 kHz. We found that this oscillation driven by transit-time instability is responsible for the shift of the IEDF of the Xe^+ ions toward the high-energy side, showing the formation of high-energy tail in the overall IEDF. It was also found that the Xe flow rate raised from 4 to 10 sccm increases the oscillation strength at the same frequency of 360 kHz, which can be applied to control of the shape of the IEDF.

MW1 89 Ion beam and performance characteristics in the presence of multiply charged ions in annular and cylindrical type Hall thruster plasmas* HOLAK KIM, YOUBONG LIM, JONGHO SEON, WONHO CHOE, *Korea Advanced Institute of Science and Technology (KAIST)* KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY (KAIST) COLLABORATION, KYUNG HEE UNIVERSITY COLLABORATION Operation performance and ion beam characteristics in the presence of multiply charged ions in cylindrical Hall thruster (CHT) and annular Hall thruster (AHT) plasmas are compared under identical conditions such as channel diameter, channel depth, and propellant flow rate. According to our previous results, the propellant utilization of the 200 W class CHT well exceeds unity [1,2] and the papers suggest that this may be related to the presence of multiply charged ions. In this work, we report the large fractions of Xe^{2+} and Xe^{3+} ions measured in the CHT plasma, which are about 16–26% and 6–7%, respectively. The measured values of specific impulse and thrust are higher by 1.4 times in CHT than in AHT at 300 V of the anode voltage, and it is found that the high fraction of multiply charged ions is responsible for the higher values of specific impulse and thrust. The details of the comparison of the overall performance and beam characteristics associated with multiply charged ions in AHT and CHT will be presented.

*This work was partly supported by the Space Core Technology Program (Grant No. 2014M1A3A3A02034510) and the Korea Institute of Materials Science (KIMS) (Grant No. 10043470).

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[2]M. Seo *et al.*, Phys. Plasmas **20**, 023507 (2013).

SESSION MR2: PLASMA INTERACTIONS WITH LIQUID
Thursday Morning, 6 November 2014; Room: State C at 8:00;

Invited Papers

8:00

MR2 1 Detection of solvated electrons at a plasma-liquid interface
DAVID B. GO, PAUL RUMBACH, DAVID BARTELS, *University of Notre Dame* R. MOHAN SANKARAN, *Case Western Reserve University*

We have recently shown that charge can be transferred from a DC microplasma jet into an aqueous solution to promote electrolytic reduction reactions [1,2]. However, the precise nature of these charge transfer reactions remains poorly understood—in particular, it is not known if plasma electrons solvate and solvated electrons are responsible for the reduction of solution species. To address these questions, we have designed and built an optical absorption spectroscopy system to directly detect solvated electrons at a plasma-liquid interface, which only have a lifetime of ~1 μs. Our preliminary results reveal that plasma electrons do indeed solvate, and survive up to depths of approximately 0.5 nm beneath the plasma-liquid interface. Adding electron scavengers such as nitrite and nitrate salts to the solution causes a decrease in optical absorption, indicating a decrease in the average lifetime of the solvated electrons, further confirming their existence. Measuring optical absorption as a function of scavenger concentration, we extrapolate rate constants that agree well with prior radiolysis experiments. These preliminary findings are consistent with the hypothesis that free electrons from atmospheric pressure plasmas solvate in aqueous solutions, and open potential applications of plasmas for solvated electron chemistry.

[1]M. Witzke, P. Rumbach, D. B. Go, and R. M. Sankaran, J. Phys. D: Appl. Phys. **45**, 442001 (2012).
[2]P. Rumbach, M. Witzke, R. M. Sankaran, and D. B. Go, J. Amer. Chem. Soc. **135**, 16264 (2013).

8:20

MR2 2 Comparison of Plasma Activation of Thin Water Layers by Direct and Remote Plasma Sources*
MARK KUSHNER, *University of Michigan*

Plasma activation of liquids is now being investigated for a variety of biomedical applications. The plasma sources used for this activation can be generally classified as direct (the plasma is in contact with the surface of the liquid) or remote (the plasma does not directly touch the liquid). The direct plasma source may be a dielectric barrier discharge (DBD) where the surface of the liquid is a floating electrode or a plasma jet in which the ionization wave forming the plasma plume reaches the liquid. The remote plasma source may be a DBD with electrodes electrically isolated from the liquid or a plasma jet in which the ionization wave in the plume does not reach the liquid. In this paper, a comparison of activation of thin water layers on top of tissue, as might be encountered in wound healing, will be discussed using results from numerical investigations. We used the modeling platform nonPDPSIM to simulate direct plasma activation of thin water layers using DBDs and remote activation using plasma jets using up to hundreds of pulses. The DBDs are sustained in humid air while the plasma jets consist of He/O2 mixtures flowed into humid air. For similar number of pulses and energy deposition, the direct DBD plasma sources produce more acidification and higher production of nitrates/nitrites in the liquid. This is due to the accumulation of NxOy plasma jets, the convective flow removes many of these species prior to their diffusing into the water or reacting to form higher nitrogen oxides. This latter effect is sensitive to the repetition rate which determines whether reactive species formed during prior pulses overlap with newly produced reactive species. in the gas phase. In the plasma jets, the convective flow removes many of these species prior to their diffusing into the water or reacting to form higher nitrogen oxides. This latter effect is sensitive to the repetition rate which determines whether reactive species formed during prior pulses overlap with newly produced reactive species.

*Work supported by National Science Foundation and Department of Energy.

8:40

MR2 3 Interaction of non-equilibrium plasma jets with liquids: chemistry, transport and biological interactions
PETER BRUGGERMAN,

9:00

MR2 4 Compensated Langmuir Probe Measurement of the Near-keeper Plasma of a Hollow Cathode Operating in Plume Mode
ZACHARY TAILLEFER, JOHN BLANDIN, *Worcester Polytechnic Institute* JAMES SZABO, *Busek Co. Inc.*

It has been reported that oscillations of the plasma potential, over a range of frequencies (⩽1 kHz–2 MHz) are related to high energy ion production in the plume of a neutralizer hollow cathode when operating in plume mode. Impact of these high energy ions with the keeper electrode face is the dominant mechanism by which electrode erosion occurs over long periods of operation (~10,000 hours). Reliable measurement of the plasma properties in this operating mode is critical

to development of computational models and efforts to mitigate the erosion and maximize lifetime of these cathodes. In this work, both plume and spot mode operating conditions of a low current ($\leqslant$5 A), dispenser hollow cathode have been quantitatively identified. An emissive probe was used to characterize the plasma potential oscillations in the near-keeper plasma during plume mode operation. Large amplitude fluctuations (exceeding 70 V) of the plasma potential were observed, at a fundamental frequency of 55 kHz, along with 2nd and 3rd harmonics. In order to measure the local electron energy distribution function (EEDF) during plume mode operation, a compensated Langmuir probe was constructed, using RF chokes, to allow accurate measurement of the EEDF and calculation of the electron temperature.

SESSION MR3: PLASMA ENHANCED CHEMICALLY REACTIVE FLOWS
Thursday Morning, 6 November 2014; Room: State D at 8:00;

Invited Papers

8:00
MR3 1 Challenges in Understanding and Predictive Modeling of Plasma Assisted Combustion
IGOR V. ADAMOVICH, WALTER R. LEMPERT, *The Ohio State University, Columbus*

8:20
MR3 2 Plasma-Based Mixing in Compressible Flow
SERGEY LENONOV, *The Ohio State University*

8:40
MR3 3 Plasma Assisted Combustion Mechanism for Small Hydrocarbons
ANDREY STARIKOVSKIY, *Princeton University*

9:00
MR3 4 Laser-Induced Plasma in Reactive Flows for Ignition and Measurements
HYUNGROK DO, CAMPBELL D. CARTER, *University of Notre Dame; Air Force Research Laboratory*

SESSION NR1: PLASMA BOUNDARIES, SHEATHS, AND BASIC PLASMA PHYSICS II
Thursday Morning, 6 November 2014; Room: State EF at 10:00; Scott Baalrud, Department of Physics, University of Iowa, presiding

Invited Papers

10:00
NR1 1 Modeling Sheaths in DC Discharges
SCOTT ROBERTSON, *University of Colorado - Boulder*

Textbook presentations on sheaths are often limited to a discussion of Bohm's criterion because more detailed analysis results in equations that can be solved only by numerical methods. There are both fluid and kinetic models for sheaths that can be solved by packaged numerical integration routines in a mathematical spreadsheet such as Mathematica, Matlab, or Mathcad. The potential profiles and the currents for sheaths at boundaries usually have monotonic profiles that are easily modeled using a Boltzmann distribution for electrons and for ions using the fluid momentum equation and the continuity equation with a source term describing plasma production. Additional ion species and bi-Maxwellian electron distributions are easily included. Virtual cathodes may form above emissive surfaces which divide the distribution function of emitted electrons into a passing population and a reflected population that can be modeled only by a kinetic approach. For sheaths at inserted objects such as probes and dust particles, it is customary to prescribe the plasma characteristics at infinity, to ignore creation of new plasma by ionization, and to solve for the radial variation of the density near the object and for the current collected by the object. A kinetic model is required for sheaths at inserted objects because the distribution function must be divided into passing particles and collected particles.

Contributed Papers

10:30

NR1 2 Electric field profiles in obstructed helium discharge PETER FENDEL, *Thorlabs* BISWA GANGULY, PETER BLETZINGER, *Air Force Research Laboratory* Axial and radial variations of electric field have been measured in dielectric shielded 25 mm diameter parallel plate electrode for 2 mA, 2250 V helium dc discharge at 1.75 Torr with 6.5 mm gap. The axial and radial electric field profiles have been measured from the polarization dependent Stark splitting of $2^1S \rightarrow 11\,^1P$ transition through collision induced fluorescence from $4^3D \rightarrow 2^3P$. The electric field values showed a strong radial variation peaking up to 5 kV/cm near the cathode radial boundary, and decreasing to about 1 kV/cm near the anode, suggesting the formation of an obstructed discharge for this low Pd condition. Also, the on-axis electric field was nearly constant across the gap indicating a radially non-uniform current density. In order to obtain information about the space charge distribution in this obstructed discharge, it was modeled using the 2-d axisymmetric Poisson solver with COMSOL finite element modeling program. The model discharge dimensions were selected to match the experimental dimensions. The best fit to the measured electric field distribution was obtained with a space charge variation of $\rho(r) = \rho_0 (r/r_0)^3$, where $\rho(r)$ is the local space charge density, ρ_0 is the maximum space-charge density, r the local radial value and r_0 the radius of the electrode.

10:45

NR1 3 Electric field measurements in a nanosecond pulse discharge by picosecond CARS/4-wave mixing BEN GOLDBERG, IVAN SHKURENKOV, IGOR ADAMOVICH, WALTER LEMPERT, *The Ohio State Univesity* Time-resolved electric field measurements in hydrogen by picosecond CARS/4-wave mixing are presented. Measurements are carried out in a high voltage nanosecond pulse discharge in hydrogen in plane-to-plane geometry, at pressures of up to several hundred Torr, and with a time resolution of 0.2 ns. Absolute calibration of the diagnostics is done using a sub-breakdown high voltage pulse of 12 kV/cm. A diffuse discharge is obtained by applying a peak high voltage pulse of 40 kV/cm between the electrodes. It is found that breakdown occurs at a lower field, 15–20 kV/cm, after which the field in the plasma is reduced rapidly due to plasma self shielding The experimental results are compared with kinetic modeling calculations, showing good agreement between the measured and the predicted electric field.

11:00

NR1 4 EEDF and Plasma Parameters of an Argon Positive Column VALERY GODYAK, BENGAMIN ALEXANDROVICH, *Retired* GEORGE PETROV, *Naval Research Laboratory* The existing experimental data base on plasma properties of the positive column in noble gases was obtained during the past century with optical spectroscopy and Langmuir probe technique. The latter is based on the assumption of a Maxwellian electron energy distribution function (EEDF). However, numerous calculations for EEDFs and experiments in Ramsauer-type gases, such as Ne, Ar, Kr and Xe, have shown Druyvesteyn-like distributions in the elastic energy range, unless strong e-e collisions at large plasma density were able to Maxwellize the EEDF. Another source of error in Langmuir probe diagnostics in Ramsauer gases is a large uncertainty in determining the plasma potential that may result in significant error in estimation of the plasma density. It has been shown [1] that the only reliable way to find basic plasma parameters in such plasmas is the EEDF measurement with plasma parameters determined as appropriate integrals of the measured EEDF. In the present work, we carried out EEDF measurements in Ar and found plasma parameters as EEDF integrals in wide ranges of pressure (1 mTorr – 1 Torr) and discharge current (3 mA -3A) in a positive column of DC discharge. The experimental results were compared with simulations based on solution of the one-dimensional electron Boltzmann equation [2] coupled with a set of equations for the plasma density and plasma potential [3]. The problems associated with EEDF measurements in DC plasmas prone to different kind of instabilities, as well as the area of the model applicability are discussed in this presentation.

[1] V. Godyak *et al.*, J. Appl. Phys. **73**, 3657 (1993).
[2] D. Uhrlandt and R. Winkler, J. Phys. D **29**, 115 (1996).
[3] U. Kortshagen *et al.*, Plasma Sources Sci. Tech. **5**, 1 (1996).

11:15

NR1 5 A self-consistent view on plasma-neutral interaction near a wall: plasma acceleration by momentum removal and heating by cold walls GERARD VAN ROOIJ, NIEK DEN HARDER, TEOFIL MINEA, AMY SHUMACK, H. DE BLANK, *FOM Institute DIFFER* PLASMA PHYSICS TEAM In plasma physics, material walls are generally regarded as perfect sinks for charged particles and their energy. A special case arises when the wall efficiently reflects the neutralized plasma particles (with a significant portion of their kinetic energy) and at the same time the upstream plasma is of sufficiently high density to yield strong neutral-ion coupling (i.e. reflected energy and momentum will not escape from the plasma). Under these conditions, plasma-surface interaction will feedback to the upstream plasma and a self-consistent view on the coupling between plasma and neutrals is required for correct prediction of plasma conditions and plasma-surface interaction. Here, an analytical and numerical study of the fluid equations is combined with experiments (in hydrogen and argon) to construct such a self-consistent view. It shows how plasma momentum removal builds up upstream pressure and causes plasma acceleration towards the wall. It also shows how energy reflection causes plasma heating, which recycles part of the reflected power to the wall and induces additional flow acceleration due to local sound speed increase. The findings are relevant as generic textbook example and are at play in the boundary plasma of fusion devices.

Invited Papers

11:30

NR1 6 Effects of Emitted Electron Temperature on the Sheath
J. P. SHEEHAN, *University of Michigan - Ann Arbor*

It has long been known that electron emission from a surface significantly affects the sheath surrounding that surface, reducing the sheath potential and electric field. Typical fluid theory of a planar sheath with emitted electrons assumes that the plasma electrons follow the Boltzmann relation and the emitted electrons are emitted with zero energy, predicting a potential drop of Te across the sheath when the surface is allowed to float. A one-dimensional kinetic theory of sheaths surrounding planar, electron-emitting surfaces is presented which accounts for plasma electrons lost to the surface and the temperature of the emitted electrons. It is shown that ratio of plasma electron temperature to emitted electron temperature significantly affects the sheath potential when the plasma electron temperature is within an order of magnitude of the emitted electron temperature. The sheath potential goes to zero as the plasma electron temperature equals the emitted electron temperature, which can occur in the afterglow of an rf plasma and some low-temperature plasma sources. These results were validated by particle-in-cell simulations. The theory was tested by making measurements of the sheath surrounding a thermionically emitting cathode in the afterglow of an rf plasma. The measured sheath potential shrunk to zero as the plasma electron temperature cooled to the emitted electron temperature, as predicted by the theory.

SESSION NR2: MAGNETICALLY ENHANCED PLASMAS

Thursday Morning, 6 November 2014
Room: State C at 10:00
Jon Gudmundsson, University of Iceland, presiding

Contributed Papers

10:00

NR2 1 Effects of anomalous transport on magnetic filter effect YEVGENY RAITSES, IGOR KAGANOVICH, *Princeton Plasma Phys Lab* ANDREI SMOLYAKOV, WINSTON FRIAS, *University of Saskatchewan, Canada* The application of the magnetic field in a low pressure plasma can cause a spatial separation of cold and hot electron groups. This so-called magnetic filter effect is not well understood and the subject of our studies. In this work, we investigate electron and ion velocity distribution functions in a low pressure plasma discharge with crossed electric and magnetic field. Previous experimental studies showed that the increase of the magnetic field leads to a more uniform profile of the electron temperature across the magnetic field. This surprising result indicates the importance of anomalous electron transport that causes mixing of hot and cold electrons. High-speed imaging revealed a coherent rotating structure with frequency of a few kHz. Theory describing coherent rotating structures and resulting anomalous transport has been developed and points to ionization and electrostatic instabilities as their possible cause [1–3]. The rotating structure affects perturbations of the plasma potential in both azimuthal and axial directions of the plasma discharge. Preliminary results of Particle-in-Cell simulations and Laser-Induced-Fluorescence measurements showed these perturbations alter the ion velocity distribution function.

[1]W. Frias, A. I. Smolyakov, I. D. Kaganovich, and Y. Raitses, Phys. Plasmas **19**, 072112 (2012).
[2]W. Frias, A. I. Smolyakov, I. D. Kaganovich, and Y. Raitses, Phys. Plasmas **2**, 052108 (2013).
[3]A. I. Smolyakov, W. Frias, I. D. Kaganovich, and Y. Raitses, Phys. Rev. Lett. **111**, 115002 (2013).

10:15

NR2 2 Optical diagnostics of sputtering in magnetically enhanced high-current discharges* DAVID SMITH, STEVEN ACETO, JASON TROTTER, TIMOTHY SOMMERER, *GE Research, Niskayuna, NY* JAMES LAWLER, *University of Wisconsin-Madison, Madison, WI* We have investigated a gallium-based liquid cathode for use in a high-voltage, high-power gas switch for grid-scale electric power conversion. The cathode requirements include conduction of high current density (1–10 A cm^{-2}), preferably at low voltage, along with minimal loss by evaporation and/or sputtering. The approach to satisfy these criteria has been to operate with a modified commercial magnetron system at high pressure where the choice of working comprises the light elements, such as hydrogen or helium. A separate anode is used to form a plane-parallel geometry. We have demonstrated pulsed operation with current densities exceeding 2 A cm^{-2} and voltages below 200 V, over a pressure range of 50–800 mTorr. The sputtering rate on gallium and other cathode materials has been estimated for various plasma conditions using a line ratio emission spectroscopy diagnostic based on analysis of the radiation trapping.

*The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

Invited Papers

10:30

NR2 3 Fluctuations, instabilities and transport in Hall plasma devices
ANDREI SMOLYAKOV, *University of Saskatchewan*

Devices with stationary, externally applied, electric field which is perpendicular to a moderate amplitude magnetic field B0, are common in magnetically controlled plasmas. High interest applications involve Penning type plasma sources, magnetrons and magnetic filters, and electric space propulsion such as Hall thrusters. The electric field produces a stationary current due to the $E0 \times B0$ electron drift, while ions do not feel the magnetic field due to their large Larmor radius. Standard drift modes doe not exist in such plasma but the $E\times B$ electron drift in inhomogeneous plasma and inertial (non-magnetized) ion response result in the so called anti-drift mode. The equilibrium electron flow destabilizes this mode and additional destabilization may come from the gradient of the magnetic field. The electron flow also result in instabilities of negative energy ion sound modes destabilized by dissipation due to collisions and sheath impedance. Sheath impedance is a result of fluctuating electric current into the sheath and further taken over by the current in the dielectric wall. Sheath impedance provide boundary conditions for ion sound wave at the boundaries of a finite length plasma. The quantitative characteristics of these instabilities and its potential ramifications for Hall devices are described.

11:00
NR2 4 Magnatron Deposition Systems
JOHN FORSTER, *Applied Materials*

Contributed Papers

11:30
NR2 5 Achievement of high atomic hydrogen densities in cylindrical rf plasmas with magnetic field URSEL FANTZ, STEFAN BRIEFI, *Max-Planck-Institut fuer Plasmaphysik* Cylindrical rf plasmas in hydrogen with and without an axial magnetic field of up to 120 G are investigated in the pressure range of 0.3 to 10 Pa. The atomic hydrogen density is determined with optical emission spectroscopy, analyzing the Balmer lines and the molecular radiation (Fulcher band). The results obtained by using different coil geometries (4 to 6 turn windings and Nagoya type antenna) as well as different diameters (10 cm and 25 cm) of a quartz, aluminum oxide or aluminum nitride cylinder are compared. RF powers of up to 600 W at a frequency of 13.56 MHz are available for the 10 cm configuration, whereas up to 70 kW power at 1 MHz are used for the 25 cm cylinder. Density ratios of atoms to molecules of up to 0.3 are achieved in both configurations, whereby the achievement in the high power setup is limited by neutral depletion. The influence of the wall material on the atomic densities, and thus the recombination coefficient, will be pointed out.

SESSION NR3: HEAVY PARTICLE COLLISIONS
Thursday Morning, 6 November 2014; Room: State D at 10:00; Michael Schulz, Missouri S&T, presiding

Invited Papers

10:00
NR3 1 Antimatter-matter scattering including rearrangement*
ALISHER KADYROV, *ARC Centre for Antimatter-Matter Studies, Curtin University, Perth, Australia*

Two distinct versions of the convergent close coupling (CCC) approach to ion-atom and ion-molecule collisions have been developed in the impact parameter representation. The first method starts from the exact three-body Schrödinger equation for the total scattering wave function and leads to coupled-channel Lippmann-Schwinger type integral equations for the transition amplitudes, with the relative motion of the heavy particles treated fully quantum mechanically. The second approach utilises a traditional semi-classical approximation. It is based on the time-dependent Schrödinger equation for the electronic part of the scattering wave function and leads to a system of coupled differential equations. This allows one to test the quality of approximations used in standard approaches to the problem. Both methods are applied to calculate antiproton collisions with inert gases and simple molecular targets in the energy range from 1 keV to 1 MeV. The methods are also applied to proton collisions including rearrangement channels. Interplay of direct ionisation and electron capture to continuum in target breakup is investigated. The first CCC calculations of the antiproton and proton stopping power in atomic and molecular hydrogen are presented.

*The work was supported by the Australian Research Council.

Contributed Papers

10:30
NR3 2 Fully Differential Study of Projectile Coherence Effects in Ionization of H2* THUSITHA ARTHANAYAKA, SACHIN SHARMA, BASU LAMICHHANE, AHAMAD HASAN, JUAN REMOLINA, SUSMITHA AKULA, DON MADISON, MICHAEL SCHULZ, *Missouri Univ of Sci & Tech* In recent years, the important role of the projectile coherence properties in ionization of H_2 has been demonstrated in measured double differential cross sections (DDCS). Here, we report the first fully differential study of such effects. The additional kinematic information was used to further "clean" the data from any background which may have survived the coincidence condition and the results show that the observed coherence effects are not just due to an experimental artifact. Furthermore, interference effects could be studied in unprecedented detail by comparing fully differential cross sections (FDCS) for a coherent and an incoherent projectile beam. For relatively small ejected electron energies we observe pronounced single-center interference, for which the molecular structure of the target is not of primary importance. Rather, this type of interference is due to a coherent superposition of different transition amplitudes leading to the same final state. However, for larger electron energies (corresponding to a speed close to the projectile speed) clear signatures of molecular two-center interference are observed in addition to single-center interference.

*This work has been supported by NSF.

10:45
NR3 3 Excitation-ionization of lithium atoms by fast ion impact: the independent-electron model and beyond* TOM KIRCHNER, NARIMAN KHAZAI, *Department of Physics and Astronomy, York University* LASZLO GULYAS, *Institute of Nuclear Research, Hungarian Academy of Sciences* We report on a

theoretical study of one-electron and two-electron processes in the ion-impact-induced ionization of lithium atoms [1]. An independent-electron model (IEM) description based on basis-generator-method and continuum-distorted-wave-eikonal-initial-state single-particle probabilities is applied to calculate 1*s* and 2*s* vacancy production single-differential cross sections, which were measured with the recently developed MOTReMi apparatus [2]. We find that the IEM predicts a considerable role of two-electron excitation-ionization processes in 1*s*-vacancy production, but is not sufficient to explain the data. Replacing the IEM by an independent-event model for one of the contributing excitation-ionization processes and also taking a shake-off process into account improves the comparison with the measurements significantly.

*This work is supported by NSERC, Canada and by OTKA, Hungary.

[1]T. Kirchner *et al.*, Phys. Rev. A **89**, 062702 (2014).
[2]D. Fischer *et al.*, Phys. Rev. Lett. **109**, 113202 (2012).

Invited Papers

11:00

NR3 4 Signatures of the electron saddle swaps mechanism in the photon spectra following charge-exchange collisions

SEBASTIAN OTRANTO, *IFISUR and Departamento de Fisica Universidad Nacional del Sur, Av. Alem 1253, 8000 Bahia Blanca, Argentina*

During the last few years, several experimental and theoretical studies have focused on state selective charge exchange processes between charged ions and alkali metals. These data are of particular importance for the tokamak nuclear fusion reactor program, since diagnostics on the plasma usually rely on charge-exchange spectroscopy. In this sense, alkali metals, have been proposed as potential alternatives to excited hydrogen/deuterium for which laboratory experiments are not feasible at present. In this talk, we present our recent work involving ion collisions with alkali metals. Oscillatory structures in the angular differential charge-exchange cross sections obtained using the MOTRIMS technique are correctly described by classical trajectory Monte Carlo simulations. These oscillations are found to originate from the number of swaps the electron undergoes around the projectile-target potential saddle before capture takes place and are very prominent at impact energies below 10 keV/amu. Moreover, cross sections of higher order of differentiability also indicate that the swaps leave distinctive signatures in the (n,l)-state selective cross sections and in the photon line emission cross sections. Oscillatory structures for the x-ray hardness ratio parameter are also predicted. In collaboration with Ronnie Hoekstra, Zernike Institute for Advanced Materials, University of Groningen and Ronald Olson, Department of Physics, Missouri University of Science and Technology.

Contributed Papers

11:30

NR3 5 Development of Ultra-Accelerated Quantum Chemical Molecular Dynamics Method for Gaseous Electronics Applications AKIRA MIYAMOTO, KENJI INABA, RYUJI MIURA, AI SUZUKI, NOZOMU HATAKEYAMA, *Tohoku University* MASAAKI MATSUKUMA, KAZUYOSHI MATSUZAKI, *Tokyo Electron Limited* TOHOKU UNIVERSITY COLLABORATION, TOKYO ELECTRON LIMITED COLLABORATION Much attention has been given to the computational design of complex chemical dynamic processes including various solid surface reactions including gaseous electronics. For this purpose we have developed novel quantum chemical molecular dynamics method called ultra-accelerated quantum-chemical molecular dynamics (UA-QCMD) method which is around 10,000,000 times faster than the conventional first principles molecular dynamics method. In the present study we demonstrated that the quantum chemical calculation in UA-QCMD, that is Colors, has high accuracy in comparison with DFT and thermodynamic data. On the basis of high speed and high accuracy calculation of the UA-QCMD method we have confirmed that the method is effective for investigating dynamic mechanism of a variety of gaseous electronics processes including oxidation process of Si crystal with O_2, H_2O and O radical, oxidation process of Ge crystal with O radical and planarization process of Ru with the gas cluster ion beam (GCIB). The calculated results have been demonstrated to agree well with experimental results and give detailed mechanism of these gaseous electronics reaction processes.

11:45

NR3 6 Electron detachment from O_2^- ions in oxygen and air in a strong electric field ALEXANDR PONOMAREV, *SSC Keldysh Research Centre, Moscow, Russia* NICKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology, Dolgoprudny, 141700, Russia* Electron detachment from O_2^- ions have been theoretically studied in oxygen and O_2-N_2 mixtures when the ions are heated in a strong external electric field. Properties of the ions were studied by a Monte Carlo simulation technique. Collisional cross sections for ion-molecule scattering was calculated on the basis of the statistical approach for the vibrational transfer and relaxation in collisions between O_2^- ions and O_2 molecules. To validate the statistical approach used, we calculated ion mobility and diffusion coefficients under conditions under which experiments are available and obtained good agreement with measurements in pure oxygen. The detachment rate was determined under the assumption that electron detachment proceeds via the formation of vibrationally excited temporary O_2^- ions. The obtained detachment rate constants turned out to agree well with available measurements in oxygen. This method was extended to calculate detachment rates in air and other O_2:N_2 mixtures. It was shown that, for a given value of the reduced electric field, the detachment rate coefficient increases with decreasing mole fraction of oxygen in mixtures. In particular, the detachment rate in air is much higher than that in oxygen. The reason is that the effect of resonant charge transfer in collisions between O_2^- and O_2 is less profound in the mixtures with lower fraction of oxygen; as a result, the average ion energy is higher.

SESSION PR1: MICRODISCHARGE DEVICES
Thursday Afternoon, 6 November 2014
Room: State EF at 13:30
Osamu Sakai, Kyoto University, presiding

Contributed Papers

13:30

PR1 1 Ignition Dynamics of a Self-pulsing y-mode discharge in a wedge-shaped micro-scaled atmospheric pressure plasma jet (μ-APPJ)* DANIEL SCHRÖDER, SEBASTIAN BURHENN, VOLKER SCHULZ-VON DER GATHEN, *Institute for Experimental Physics II, Ruhr-Uni Bochum* Microplasma jets, operated at atmospheric pressure, are susceptible to instabilities. A prominent one is the "α-γ transition" instability, often resulting in a constricted discharge at high gas temperatures destroying the device. Thus a safe and stable application of these devices for treating heat-sensitive biological materials is limited. In order to analyze the responsible mechanisms for this mode transition, the capacitative coupled, rf-excited (f = 13.56 MHz) micro-scaled plasma jet (μ-APPJ) has been modified. A wedge-shaped electrode configuration has been developed, forming a 30 mm long discharge gap increasing linearly from 1 mm at the gas inlet to 3 mm at the nozzle. A self-pulsing behavior is observed characterized by a periodical ignition of a constricted y-mode discharge feature at the gas inlet, propagating with the gas flow through the device towards the nozzle. Spectral- and phase-resolved optical emission spectroscopy (PROES) is applied to investigate discharge ignition dynamics and cross-checked with synchronized current /voltage measurements.

*We gratefully acknowledge the support by "Deutsche Forschungsgemeinschaft" in the frame of Research Unit FOR1123 'Physics of Microplasmas' and by the Research Department "Plasma with Complex Interactions".

13:45

PR1 2 The formation of a turbulent front in a time modulated argon APPJ* SHIQIANG ZHANG, EDDIE VAN VELDHUIZEN, *Department of Applied Physics, Eindhoven University of Technology, the Netherlands* PETER BRUGGEMAN, *University of Minnesota, Department of Mechanical Engineering, 111 Church Street SE, Minneapolis, MN 55455, U.S.A.* ANA SOBOTA, *Department of Applied Physics, Eindhoven University of Technology, the Netherlands* Cold atmospheric pressure plasma jets (APPJ) are promising tools for biomedical applications such as wound healing, disinfection, decontamination, and material processing. The jet effluent is blown in an open air environment which leads to air diffusion and argon-air mixtures in the effluent flow. Since the reactive species carried by the flow are important in such kinds of applications, knowledge of the characteristics of the flow are crucial for understanding the distribution, evolution, transport, and chemical reactions of these reactive species. The flow dynamics of an non equilibrium argon-based atmospheric pressure plasma jet (APPJ) is investigated in this work. Shadowgraphy results show that turbulent front appears when the plasma is switched on and off and the laminar length of the flow during the plasma on phase is shorter than that during the plasma off phase. Time resolved gas temperature profiles obtained by Rayleigh scattering are used to explain the formation of the turbulent front when the plasma is switched on and off and the reduction of the length of the laminar flow.

*The funding is partly from STW.

14:00

PR1 3 Dynamics of a Microwave Excited Microplasma Flowing into Very Low Pressures* PENG TIAN, *University of Michigan* MARK DENNING, RANDALL URDAHL, *Agilent Technologies* MARK J. KUSHNER, *University of Michigan* Capacitively coupled microplasmas in dielectric cavities have a range of applications from VUV sources for surface treatment to radical production. Due to the small size of these devices, pd (pressure $\times$ size) scaling requires that they operate at high pressure. When the output of the microplasma is needed at low pressure, a plume of radicals and ions flows from the higher pressure microdischarge cavity into the lower pressure workspace. These conditions affect both the delivery of the radicals, ions and photons in the plume, and the dynamics of the microdischarge. In this paper, we discuss results from a computational investigation of a microwave excited microplasma operating at a pressure of several Torr of a rare gas with powers of 2–10s of Watts at 2.5 GHz. The plume from the microdischarge cavity flows into pressures as low as a few mTorr. A 2-d plasma hydrodynamics model with radiation and electron energy transport addressed using Monte Carlo techniques has been modified to enable the plume to flow into near vacuum. Plasma dynamics and reactive fluxes from the cavity will be discussed for different flow boundary conditions, as a function of power, pressure and gas mixtures.

*Work supported by Agilent Technologies, DOE Office of Fusion Energy Science and NSF.

14:15

PR1 4 Interaction of High-Frequency Electromagnetic Waves with Pre-Breakdown Atmospheric Pressure Micro-Discharge Region* ABBAS SEMNANI, DIMITRIOS PEROULIS, *Purdue University* The properties of a micro-scale gap at atmospheric pressure are completely different in pre- and post-breakdown conditions [1]. Unlike the quasi-neutral region formed after breakdown, the ion number density is orders of magnitude higher than the electron density in pre-breakdown conditions [2]. Consequently, ions may also contribute on the discharge conductivity even though they are much heavier than electrons. In this work, we study the interaction of high frequency electromagnetic waves with the discharge region before and after breakdown. The study is done at room temperature and atmospheric pressure conditions with gaps in the order of hundreds of nanometers up to a few micrometers. Gas discharge simulations are performed by using the PIC/MCC technique while the finite difference time domain (FDTD) method is used for electromagnetic simulations. The species are imported into EM simulations by a conduction current term in Ampere's law. The validity of conventional wisdom of ignoring the ions' contribution is examined for different cases.

*This paper is based upon work supported by the National Science Foundation under Grant No. ECCS-1202095.

[1] A. Semnani *et al.*, Appl. Phys. Lett. **102**, 174102 (2013).
[2] A. Venkattraman *et al.*, Phys. Plasmas **19**, 123515 (2012).

14:30

PR1 5 Fluid modeling of operating modes in a field emission driven alternating current (FEDAC) microdischarge AYYASWAMY VENKATTRAMAN, ARGHAVAN ALAMATSAZ, THERAZHUNDUR RAMESH SHIVAPRASAD, *Univ of California - Merced* The recent interest in electrostatic microscale devices has lead to a great emphasis on electrical breakdown of gases in microgaps. The breakdown process has been shown to be significantly different from its counterpart in macrogaps with field emission of electrons from the cathode playing a major role. This work aims to build on prior work dealing with pre-breakdown and post-breakdown operating modes in direct current field emission driven (FED) microdischarges. Specifically, charged particle dynamics in microscale gaps that are driven by time-varying fields are studied using an in-house two-fluid code with appropriate cathode boundary conditions including field emission. The model includes continuity and energy equations for both electrons and ions to account for the significant non-equilibrium and is augmented by the Poisson's equation for electrostatic potential. The frequency dependence of breakdown behavior as well as pre-breakdown and post-breakdown current-voltage characteristics is determined for a wide range of frequencies from low radio frequency (RF) to microwave and contrasted with existing results for direct current FED microdischarges. The results are also used to explain trends recently observed in an evanescent-mode cavity resonator operating in the microwave regime.

14:45

PR1 6 Quantum Simulation of Field Emission in Microscale Gas Discharges* YINGJIE LI, DAVID GO, *University of Notre Dame* Field emission can be a critical cathode process in microscale gas discharges, especially for electrode gaps less than 10 μm. In this work, ion-enhanced field emission is determined by solving the one-dimensional Schrodinger's equation. In most prior work, a linear approximation for the ion potential has been coupled with the Fowler-Nordheim equation, but this does not realistically account for the form of potential barrier, and underestimates the impact of the ion's potential well. Here, the tunneling behavior is more accurately represented by determining the wave function of the electrons inside and outside of the cathode in order to predict the emission current. Using this approach, microscale breakdown theory is revisited, in order to understand the deviation from classic breakdown theory at microscale dimensions.

*This material is based upon work supported by the Air Force Office of Scientific Research under AFOSR Award No. FA9550-11-1-0020.

SESSION PR2: PLASMA DEPOSITION AND NANOPARTICLE GENERATION
Thursday Afternoon, 6 November 2014
Room: State C at 13:30
Kazuo Takahashi, Kyoto Institute of Technology, presiding

Contributed Papers

13:30

PR2 1 Surface modifications by plasma produced nanoparticles* JOHANNES BERNDT, PASCAL BRAULT, *GREMI UMR 7344 CNRS & Universite d'Orleans* Low temperature plasmas with their distinct non equilibrium character are a versatile tool for the production and subsequent deposition of nanoparticles. This contribution will focus on two aspects: on strategies to control the formation of nanoparticles in reactive low temperature plasmas and on the production and functionalization of nanoparticle- deposits. The importance of such nanoparticle-deposits will be discussed on the basis of two examples: the production of surfaces with switchable wetting properties and the decoration of surfaces with nanoparticles for fuel cell applications.

*The financial support of the European Commission under the FP7 Fuel Cells and Hydrogen Joint Technology Initiative Grant Agreement FP7-2012-JTI-FCH-325327 for the SMARTCat project is gratefully acknowledged.

13:45

PR2 2 Nickel Nanoparticles Production using Pulsed Laser Ablation under Pressurized CO_2 MARDIANSYAH MARDIS, NORIHARU TAKADA, *Nagoya University* SITI MACHMUDAH, *Sepuluh Nopember Institute of Technology* WAHYU DIONO, HIDEKI KANDA, *Nagoya University* KOICHI SASAKI, *Hokkaido University* MOTONOBU GOTO, *Nagoya University* We used nickel (Ni) plate as a target and irradiated pulse laser ablation with a fundamental wavelength of 1064 nm under pressurized CO_2. The Ni plate was ablated at various pressure (5–15 MPa), temperature (15–80°), and irradiation time (3–30 min). The method successfully generated Ni nanoparticles in various shape and size. Generated Ni nanoparticles collected on a Si wafer and the ablated Ni plate were analyzed by Field Emission Scanning Electron Microscope (FE-SEM). With changing pressure and temperature, the structures of Ni nanoparticles also changed. The shape of generated particles is sphere-like structure with diameter around 10–100 nm. Also it was observed that a network structure of smaller particles was fabricated. The mechanism of nanoparticles fabrication could be explained as follows. Ablated nickel plate melted during the ablation process and larger particles formed, then ejected smaller spherical nanoparticles, which formed nanoclusters attached on the large particles. This morphology of particles was also observed for gold and silver nanoparticles with same condition. Further, the optical emission intensity from ablation plasma and the volume of the ablated crater were also examined under pressurized CO_2.

Invited Papers

14:00

PR2 3 Plasmas for controlling the synthesis of semiconductor nanocrystals
REBECCA ANTHONY, *Department of Mechanical Engineering, Michigan State University*

Recently, nonthermal plasma synthesis of opto-electronically active semiconductor nanomaterials has attracted interest. The plasma reactor is especially attractive for synthesis of some earth-abundant and nontoxic semiconductor nanocrystals (NCs), such as silicon and gallium nitride. These materials, with high melting temperatures, are more challenging to grow using the liquid-phase techniques that are successful for other materials, such as II-VI NCs. Here, plasma synthesis of high-quality NCs from these materials will be discussed, including investigations on controlling the NCs' light emission properties via physical changes in the NCs brought about by altering the plasma parameters. For example, nanoparticle crystallinity may be controlled by altering the power supplied to the plasma reactor, which has been revealed to influence both the density of atomic hydrogen and the ion density in the plasma. In addition, the surfaces of NCs (which have been shown to be crucial in determining NC luminescence properties) can be altered utilizing reactions that take place in the plasma after NC growth is finished. The features of the plasma reactor provide unique and selective control over the properties of NCs, and also allow for deposition of dense films of NCs directly from the gas-phase, in complete avoidance of liquid-phase methods. These features - crystallization of environmentally benign materials, capacity to control NC surfaces via plasma-intiated reactions, and direct deposition of these materials onto device substrates – unite in a method for "green" processing of nanomaterials. Future directions for utilizing plasma reactors for nanomaterials synthesis and processing will also be discussed.

Contributed Papers

14:30

PR2 4 Novel method of Ge crystalline thin film deposition on SiO2 by sputtering* MASAHARU SHIRATANI, DAIKI ICHIDA, HYUNWOONG SEO, NAHO ITAGAKI, KAZUNORI KOGA, *Kyushu University* We are developing a novel method of Ge crystalline thin film deposition on SiO_2 by sputtering. For the method, very thin Au films were deposited on SiO_2 substrates and then Ge atoms were irradiated to the Au films by sputtering. By EDX and SEM measurements, we found two kinds of Ge film growth: one is Ge film formation on Au films for a high flux irradiation of Ge, and the other is Ge film formed between Au films and SiO_2 substrates for a relatively low flux irradiation of Ge. The latter film formation is useful to create high quality Ge crystalline films on various kinds of substrate with aligned crystal orientation and a large grain size. XRD and Raman measurements show the films are Ge crystal and the better crystallinity for the higher substrate temperature. Surface morphology depends on the substrate temperature. At 180–250 C Ge islands of 50 nm in diameter are formed on surface. Smooth Au films are obtained at 320 C. Au aggregates of 100 nm in diameter are formed on surface at 400 C. The Ge films show a high absorption coefficient for a wide light wavelength range from 400 nm to 1100 nm and photo generated current in the same wavelength range.

*Work supported by JSPS.

14:45

PR2 5 Surface modification due to atmospheric pressure plasma treatment during film growth of silicon dioxide like and amorphous hydrogenated carbon material* KATJA RUEGNER, RUEDIGER REUTER, ACHIM VON KEUDELL, JAN BENEDIKT, *Ruhr-Uni Bochum, RD Plasmas with Complex Interactions* Plasma deposition of silicon dioxide (SiO_2) or amorphous hydrogenated carbon (a-C:H) at atmospheric pressure is a promising tool for industrial applications. SiO_2 is used as scratch resistant layers, as protection against corrosion or as gas diffusion barrier layers. a-C:H is of special interest due to its optical, electrical, biocompatible and mechanical properties, which are tunable, depending on the bonding state of carbon. Besides the deposition of material, atmospheric pressure plasma jets (APPJ) can be used to modify the surface of the deposited films during their growth. Deposition and the treatment are realized in the same chamber, were both jets face a rotating substrate. Therefore, deposition and treatment of the same trace can be performed in an alternating manner. Further, in-situ FTIR is applied. For the deposition an APPJ with two parallel electrodes is used, operating with either He/HMDSO in the case of SiO_2 deposition or He/C_2H_2 in the case of a-C:H deposition. For the treatment either the APPJ or a coaxial jet with different gas mixtures is used. For the deposition of SiO_2-like films the treatment with a He/O_2, a He/N_2, and an Ar plasma during the film growth have shown significant changes in the film structure. The influence of treatments on a-C:H film is currently under investigation.

*The project is supported by the German Research Foundation (DFG) in the research group FOR 1123.

15:00

PR2 6 Comparison of sticking probabilities of metal atoms in magnetron sputtering deposition of CuZnSnS films K. SASAKI, S. KIKUCHI, *Hokkaido University* In this work, we compared the sticking probabilities of Cu, Zn, and Sn atoms in magnetron sputtering deposition of CZTS films. The evaluations of the sticking probabilities were based on the temporal decays of the Cu, Zn, and Sn densities in the afterglow, which were measured by laser-induced fluorescence spectroscopy. Linear relationships were found between the discharge pressure and the lifetimes of the atom densities. According to Chantry [1], the sticking probability is evaluated from the extrapolated lifetime at the zero pressure, which is given by $2l_0(2-\alpha)/(\bar{v}\alpha)$ with α, l_0, and $\bar{v}$ being the sticking probability, the ratio between the volume and the surface area of the chamber, and the mean velocity, respectively. The ratio of the extrapolated lifetimes observed experimentally was $\tau_{Cu}:\tau_{Sn}:\tau_{Zn} = 1:1.3:1$. This ratio coincides well with the ratio of the reciprocals of their mean velocities ($1/\bar{v}_{Cu}:1/\bar{v}_{Sn}:1/\bar{v}_{Zn} = 1.00:1.37:1.01$). Therefore, the present experimental result suggests that the sticking probabilities of Cu, Sn, and Zn are roughly the same.

[1]P. J. Chantry, J. Appl. Phys. **62**, 1141 (1987).

15:15

PR2 7 RF Magnetron Sputtering Deposited W/Ti Thin Film For Smart Window Applications LUTFI OKSUZ, MELEK KIRISTI, FERHAT BOZDUMAN, AYSEGUL UYGUN OKSUZ, *Suleyman Demirel University* Electrochromic (EC) devices can change reversible and persistent their optical properties in the visible region (400–800 nm) upon charge insertion/extraction according to the applied voltage. A complementary type EC is a device containing two electrochromic layers, one of which is anodically colored such as vanadium oxide (V_2O_5) while the other cathodically colored such as tungsten oxide (WO_3) which is separated by an ionic conduction layer (electrolyte). The use of a solid electrolyte such as Nafion eliminates the need for containment of the liquid electrolyte, which simplifies the cell design, as well as improves safety and durability. In this work, the EC device was fabricated on a ITO/glass slide. The WO_3-TiO_2 thin film was deposited by reactive RF magnetron sputtering using a 2-in W/Ti (9:1%wt) target with purity of 99.9% in a mixture gas of argon and oxygen. As a counter electrode layer, V_2O_5 film was deposited on an ITO/glass substrate using V_2O_3 target with the same conditions of reactive RF magnetron sputtering. Modified Nafion was used as an electrolyte to complete EC device. The transmittance spectra of the complementary EC device was measured by optical spectrophotometry when a voltage of ± 3 V was applied to the EC device by computer controlled system. The surface morphology of the films was characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM) (Fig. 2). The cyclic voltammetry (CV) for EC device was performed by sweeping the potential between ± 3 V at a scan rate of 50 mV/s.

SESSION PR3: CORONAL AND HV DISCHARGES
Thursday Afternoon, 6 November 2014
Room: State D at 13:30
Brooke Stutzman, U.S. Coast Guard Academy, presiding

Contributed Papers

13:30
PR3 1 Temporal evolution of the electron density produced by nanosecond repetitively pulsed discharges in water vapor at atmospheric pressure FLORENT SAINCT, DEANNA LACOSTE, *EM2C laboratory* MICHAEL KIRKPATRICK, EMMANUEL ODIC, *Supelec-E3S* CHRISTOPHE LAUX, *EM2C laboratory* A study of plasma discharges produced by nanosecond repetitive pulses (NRP) in water vapor at 450 K and 1 atm is presented. The plasma was generated between two point electrodes with 20-ns duration, high-voltage (0–20 kV) pulses, at a repetition frequency of 10 kHz, in the spark regime (2 mJ/pulse). Atomic lines measured by optical emission spectroscopy were used to determine the electron number density in this non-equilibrium water-vapor plasma. The broadenings and shifts of the H_α and H_β lines of the hydrogen Balmer series and of the atomic oxygen triplet at 777 nm were analyzed. For a maximum reduced electric field of about 200 Td, a maximum electron density of 2×10^{18} cm^{-3} was measured, corresponding to an ionization level of about 10%. This ionization level is two orders of magnitude higher than the one obtained for similar NRP discharges in air at atmospheric pressure.

13:45
PR3 2 Fast-imaging and spectroscopic analysis of atmospheric argon streamers for large gap arc breakdown* MICHAEL PACHUILO, FRANCIS STEFANI, ROGER BENGTSON, LAXMINARAYAN RAJA, *Univ of Texas, Austin* A non-equilibrium plasma source has been developed to assist in the low-voltage arc breakdown of large electrode gaps. The source consists of a dielectric embedded wire helically wound around a confining cylindrical quartz chamber. Annular electrodes cap the ends of the quartz chamber. An argon feed gas is used to provide a uniform environment and exhausts to ambient atmospheric conditions. A negative polarity 50 kV trigger pulse is applied to the embedded trigger wire to initiate the arc breakdown. Application of the trigger pulse produces a localized coronal discharges along the inner surface of the quartz tube. The corona provides seed electrons through which streamers propagate from one of the main discharge electrode along the quartz surface until it reaches the opposite electrode to bridge the gap. Once the gap is bridged a spark over occurs and robust arc discharge is formed in the chamber volume. Fast imaging of the streamer propagation establishes its velocity in the range of ~ 100 km/s. Spectroscopy of the streamer discharge in atmospheric argon has been conducted and electron temperature and number density estimated from a collision radiative model. Argon spectrum is dominated by neutral argon lines in the 650–950 nm range, and singly ionized argon lines are observed in the ultra-violet to near UV (300–400 nm).

*Research was performed in connection with AFOSR Contract FA9550-11-1-0062.

14:00
PR3 3 The role of oxygen and nitrogen metastable states in the electrical breakdown of air JOHN LOWKE, *CSIRO Materials Science and Engineering* For the initial formation of an electrical discharge in air, an electric field of approximately 25 kV/cm is required at a pressure of 1 bar, corresponding to a value of E/N of ~100 Td; E is the electric field strength and N the gas number density. Below 100 Td, rates of electron attachment to form negative ions are greater than for ionization, so that a discharge of electrons is impossible. However, in less than a microsecond, metastable molecules of oxygen and nitrogen are produced, which markedly change the character of the discharge. The singlet delta metastable state of oxygen detaches electrons from negative ions of oxygen. By far the largest collisional process is the production of the metastable vibrational states of nitrogen. Populations of these states become so large that there is a significant increase in electron energy through collisions of these states with low-energy electrons. Solutions have been obtained of the Boltzmann transport equation for various values of E/N to obtain rates of production of the various metastables. It is found that the effect of the metastable states of nitrogen increases the electron energy at low values of E/N by orders of magnitude, ionization still being significant at E/N = 20 Td. An analysis is made of continuity equations of electrons, ions and metastables and it is concluded that sustaining fields during the electrical breakdown process can be as low as 5 kV/cm at 1 bar, or an E/N of 20 Td, which is a reduction of a factor of five from the initial breakdown fields.

14:15
PR3 4 Back corona enhanced organic film deposition inside an Atmospheric Pressure Weakly Ionized Plasma reactor ROKIBUL ISLAM, SHUZHENG XIE, KARL ENGLUND, PATRICK PEDROW, *Washington State University* A grounded screen with short needle-like protrusions has been designed to generate back corona in an Atmospheric Pressure Weakly Ionized Plasma (APWIP) reactor. The grounded screen with protrusions is placed downstream at a variable gap length from an array of needles that is energized with 60 Hz high voltage. The excitation voltage is in the range 0–10 kV RMS and the feed gas mixture consists of argon and acetylene. A Lecroy 9350AL 500 MHz digital oscilloscope is used to monitor the reactor voltage and current using a resistive voltage divider and a current viewing resistor, respectively. The current signal contains many positive and negative current pulses associated with corona discharge. Analysis of the current signal shows asymmetry between positive and negative corona discharge currents. Photographs show substantial back corona generated near the tips of the protrusions situated at the grounded screen. The back corona activates via bond scission acetylene radicals that are transported downstream to form a plasma-polymerized film on a substrate positioned downstream from the grounded screen. The oscillograms will be used to generate corona mode maps that show the nature of the corona discharge as a function of gap spacing, applied voltage and many other reactor parameters.

14:30
PR3 5 Plasma decay in O_2-containing mixtures after high-voltage nanosecond discharge NICKOLAY ALEKSANDROV, EVGENY ANOKHIN, SVETLANA KINDYSHEVA, *Moscow Institute of Physics and Technology, Dolgoprudny, 141700, Russia* ANDREY STARIKOVSKIY, *Princeton University, Princeton, USA* Plasma decay after a high-voltage nanosecond discharge has been studied experimentally and numerically in O_2:Ar, O_2:CO_2 and some other mixtures for room gas temperature and pressures between 1 and 10 Torr. Time-resolved electron density history was measured by a microwave interferometer for initial electron densities in the range (1–3) $\times$ 10^{12} cm^{-3} and the effective electron-ion recombination coefficient was determined. A numerical simulation was carried out to describe the temporal evolution of the densities of charged particles under the conditions considered. The balance equations for these particles were solved simultaneously with the

equation for electron effective temperature. It was shown that the loss of electrons in this case is determined by dissociative and three-body electron recombination with O_2^+ ions. The rate coefficient of three-body electron recombination was determined for these molecular ions. When changing gaseous mixture composition, the frequency of electron energy relaxation was varied by many orders of magnitude. This allowed extracting the values of three-body electron-ion recombination for both thermalized and heated electrons.

14:45

PR3 6 NO density and gas temperature measurements in atmospheric pressure nanosecond repetitively pulsed (NRP) discharges by Mid-IR QCLAS* MARIEN SIMENI SIMENI, GABI-DANIEL STANCU, CHRISTOPHE LAUX, *Laboratory EM2C, Ecole Centrale Paris* Nitric oxide is a key species for many processes: in combustion, in human skin physiology... Recently, NO-ground state absolute density measurements produced by atmospheric pressure NRP discharges were carried out in air as a function of the discharge parameters, using Quantum Cascade Laser Absorption Spectroscopy. These measurements were space averaged and performed in the post-discharge region in a large gas volume. Here we present radial profiles of NO density and temperature measured directly in the discharge for different configurations. Small plasma volume and species densities, high temperature and EM noise environment make the absorption diagnostic challenging. For this purpose the QCLAS sensitivity was improved using a two-detector system. We conducted lateral absorbance measurements with a spatial resolution of 300 μm for two absorption features at 1900.076 and 1900.517 cm^{-1}. The radial temperature and NO density distributions were obtained from the Abel inverted lateral measurements. Time averaged NO densities of about 1.E16 cm^{-3} and gas temperature of about 1000K were obtained in the center of the discharge.

*PLASMAFLAME Project (Grant No ANR-11-BS09-0025).

SESSION QR1: PLASMA MODELING AND SIMULATIONS II

Thursday Afternoon, 6 November 2014
Room: State EF at 15:30
Timo Gans, University of York, Department of Physics, presiding

Contributed Papers

15:30

QR1 1 RF plasma conductivity in the CERN Linac4 H$^-$ ion source, comparison of simulations and measurements STEFANO MATTEI, *CERN, 1211 Geneva 23, Switzerland* SHINTARO MOCHIZUKI, KENJIRO NISHIDA, TAKANORI SHIBATA, *Graduate school of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kouhoku-ku, Yokohama 223-8522, Japan* JACQUES LETTRY, *CERN, 1211 Geneva 23, Switzerland* AKIYOSHI HATAYAMA, *Graduate school of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kouhoku-ku, Yokohama 223-8522, Japan* MINH QUANG TRAN, *Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Federale de Lausanne, CH-1015 Lausanne, Switzerland* CERN Linac4 H$^-$ ion source is a Radio Frequency Inductively Coupled Plasma (RF-ICP) ion source. A solenoid antenna of 4 to 6 turns heats the plasma at a frequency of 2 MHz, in pulses of 0.5 ms and with a repetition rate of 0.8 to 2 Hz. In order to investigate the underlying plasma physics we have developed a Particle-In-Cell Monte Carlo Collision (PIC-MCC) code with the long-term goal to optimize the ion source operational parameters and geometry. This paper presents the determination of the complex plasma conductivity based on the PIC-MCC simulations. The resistive and reactive components of the plasma conductivity are computed as the proportionality factor between the RF electric field and the resulting plasma current. We present a parametric investigation as a function of the antenna current, gas pressure and antenna geometry. The simulation results, corresponding to the Linac4 ion source, are compared to the time-resolved optical emission photometry measurements of the Balmer lines obtained on a dedicated ion source test stand.

15:45

QR1 2 A Fast Four Fluid Model of Electronegative Plasmas Including Non-Isothermal Neutrals* ANDREW HURLBATT, TIMO GANS, DEBORAH O'CONNELL, *York Plasma Institute, Department of Physics, University of York, Heslington, York, YO10 5DD* A novel semi-analytical fluid model has been developed of a four component plasma consisting of positive ions, negative ions, non-maxwellian electrons and non-isothermal neutrals. The four dominant interspecies reactions are considered, as well as elastic collisions between charged and neutral species. The model is based on an idealised RF discharge with an infinite planar geometry, and provides time averaged spatial profiles of species densities and fluxes, as well as neutral gas temperature, within the plasma bulk and presheath. Due to the combination of boundary conditions and normalisations, only the mean electron energy and the relative electron density are required as input parameters. The pressure length product of the system is given as an output, meaning the model can be scaled to any plasma discharge sharing geometrical characteristics. Despite the increased complexity and reduced assumptions compared with other similar electronegative models, analyticity is maintained until the point of spatial integration. This means the computation time is on the order of seconds, allowing the detailed investigation of discharge properties on phenomena such as Neutral Gas Depletion and electronegative to electropositive transitions over large regions of parameter space.

*EPSRC EP/K018388/1.

16:00

QR1 3 Uncertainty and error in complex plasma chemistry models MILES TURNER, *Dublin City University* Plasma chemistry models commonly contain hundreds if not thousands of parameters, in the way of rate constants and other related coefficients. None of these parameters is exactly known. Moreover, in modern models, the parameters have often been transmitted from the primary data sources by complex and error prone routes. Consequently, typical plasma chemistry models embody unavoidable uncertainty, because of inexact knowledge of the parameters, and some margin of avoidable error, because of faulty transmission. This paper discusses a model for helium/oxygen mixtures (a moderately complex model with some 350 reactions), in which all the the rate constants have been traced to primary sources, with the initial aim of determining the uncertainty associated with each parameter. This data is then used in a Monte Carlo procedure to investigate the resulting uncertainty in the model predictions. Uncertainty is found to be unequally distributed across the model outputs, but for some results it is a factor of several or more. This certainly needs to be considered when comparing model calculations with experiments, or deciding whether conclusions drawn from the model predictions are robust. The process of tracing the sources for the rate constants shows that some of them have been polluted by various types of error. Some examples will be discussed.

16:15

QR1 4 Development, Verification and Validation of VizArc: a General-Purpose Thermal Plasma Simulation Tool SHANKAR MAHADEVAN, DOUG BREDEN, *Esgee Technologies, Inc.* LAXMINARAYAN RAJA, *The University of Texas at Austin* This work describes a recently developed general-purpose simulation tool (VizArc) for computational modeling of thermal (arc) plasmas. These plasmas typically exist in systems where the pressures range from 0.1–10 atm and with temperatures ranging from about 1000 K to ~10,000's K. VizArc solves a coupled set of non-linear governing equations that describe physical and chemical phenomena in multi-species, single-temperature, quasi-neutral plasma. Governing equations for the flow and electromagnetic quantities in the gas and heat transfer in solids are included. Applications include the modeling of spark discharges, HID lamps, circuit breakers and welding/spray coating. Verification and validation, which are essential aspects of computational code development, are discussed. The steps involved in verification and validation of the new model are described, including component-wise verification, a grid convergence study, parallel implementation verification, and comparison of model results with experimental results from the literature.

16:30

QR1 5 An Analytical Study of the Mode Propagation along the Plasmaline* DANIEL SZEREMLEY, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, DENIS EREMIN, *None* THEORETICAL ELECTRICAL ENGINEERING TEAM The market shows in recent years a growing demand for bottles made of polyethylene terephthalate (PET). Therefore, fast and efficient sterilization processes as well as barrier coatings to decrease gas permeation are required. A specialized microwave plasma source – referred to as the plasmaline – has been developed to allow for treatment of the inner surface of such PET bottles The plasmaline is a coaxial waveguide combined with a gas-inlet which is inserted into the empty bottle and initiates a reactive plasma. To optimize and control the different surface processes, it is essential to fully understand the microwave power coupling to the plasma inside the bottle and thus the electromagnetic wave propagation along the plasmaline. In this contribution, we present a detailed dispersion analysis based on an analytical approach. We study how modes of guided waves are propagating under different conditions (if at all). The analytical results are supported by a series of self-consistent numerical simulations of the plasmaline and the plasma.

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

16:45

QR1 6 Self-consistent simulation of a microwave coaxial plasma waveguide ROCHAN UPADHYAY, *Esgee Technologies Inc.* LAXMINARAYAN RAJA, *The University of Texas at Austin* Microwave discharges are typically useful for generating high density, non-equilibrium plasmas at relatively low electron temperature. Recently there has been much interest in Coaxial Plasma Waveguides (CPW) for large area deposition and etching. In a CPW, microwave propagates between a metallic or dielectric surface and a plasma that acts as an outer conductor. The plasma is sustained by surface wave heating due to the microwave propagating in the waveguide. Most studies of this phenomenon have focused on understanding of the electromagnetic surface wave, its dispersion characteristics and power deposition. The plasma is typically modelled as quasi-neutral and sheath effects are either neglected or represented using simplified analytical models. This approach usually precludes the analysis of important effects like self-bias, imposed DC or RF bias on the electrodes, electrostatic waves and the influence of sheath voltage on charged species transport and/or reaction rates. In this study we simulate a CPW using a fully self-consistent model. The model uses the electrostatic and magnetic vector potential equations that are fully coupled with the plasma governing equations to model the electromagnetic effects. This allows us to study sheath effects in conjunction with the surface wave phenomena at microwave frequencies. We compare results with a simplified model that assumes a quasi-neutral plasma that neglects the sheath. We also discuss the range of applicability of simplified models.

17:00

QR1 7 Electron acceleration due to the two-stream instability of ion and electron beams propagating in background plasma IGOR KAGANOVICH, *Princeton Plasma Phys Lab* DMYTRO SYDORENKO, *Department of Physics, University of Alberta, Canada* Intense electron or ion beams propagating in plasmas are subject to the two-stream instability, which leads to a slowing down of the beam particles, acceleration of the plasma particles, and transfer of the beam energy to the plasma particles and wave excitations. Making use of the particle-in-cell codes EDIPIC and LSP, we have simulated two-stream instability interactions over a wide range of beam and plasma parameters. Typically, the instability saturates due to nonlinear wave-trapping effects of either the beam particles or plasma electrons. The saturation due to nonlinear wave-trapping effects limits the "mixing" in phase-space and may produce coherent structures in the electron velocity distribution function. For the case of an electron beam, simulations show that the two-stream instability is intermittent, with quiet and active periods. During the active periods of the two-stream instability, the beam interacts with the plasma most intensively at locations where the global frequency of the instability matches the local electron plasma frequency. These intense localized plasma oscillations produce peaks in the velocity distribution function similar to the ones measured in the experiment [1].

[1]L. Xu *et al.*, Appl. Phys. Lett. **93**, 261502 (2008).

17:15

QR1 8 Transport and radiation in complex LTE mixtures* JESPER JANSSEN, *Eindhoven University of Technology* KIM PEERENBOOM, *Université libre de Bruxelles* JOS SUIJKER, *Philips Lighting* MYKHAILO GNYBIDA, *Eaton European Innovation Center* JAN VAN DIJK, *Eindhoven University of Technology* Complex LTE mixtures are for example encountered in re-entry, welding, spraying and lighting. These mixtures typically contain a rich chemistry in combination with large temperature gradients. LTE conditions are also interesting because they can aid in the validation of NLTE algorithms. An example is the calculation of transport properties. In this work a mercury free high intensity discharge lamp is considered. The investigation focusses on using salts like InI or SnI as a buffer species. By using these species a dominant background gas like mercury is no longer present. As a consequence the diffusion algorithms based on Fick's law are no longer applicable and the Stefan-Maxwell equations must be solved. This system of equations is modified with conservation rules to set a coldspot pressure for saturated species and enforce the mass dosage for unsaturated species. The radiative energy transport is taken into account by raytracing. Quantum mechanical simulations have been used to calculate the potential curves and the transition dipole moments for indium with iodine and tin with iodine. The results of these calculations have been used to predict the quasistatic broadening by iodine.

*The work was supported by the project SCHELP from the Belgium IWT (Project Number 110003) and the CATRENE SEEL Project (CA502).

THURSDAY AFTERNOON \ QR1

SESSION QR2: PLASMA APPLICATIONS IN ACCELERATOR TECHNOLOGY

Thursday Afternoon, 4 November 2014; Room: State D at 15:30; Keith Cartwright, Sandia National Laboratory, presiding

Invited Papers

15:30

QR2 1 The Grand Challenges for Engineering in the 21st

THOMAS KATSOULEAS, *Dean, Duke Pratt School of Engineering*

The Grand Challenges for Engineering in the 21st century identified by the NAE re-frame the engineering profession in human facing terms rather than in terms of disciplines or devices. Nevertheless, plasmas will play a major role in solving many of these challenges. The challenges involve making the world more sustainable, more healthful, more secure and more joyful. From the challenge of Provide Clean Water (to nearly a billion people who lack regular access to it), to Provide Energy from Fusion and Engineer the Tools of Scientific Discovery, plasmas will play an essential role. This talk highlights progress on the NAE Grand Challenges and the role that plasmas are playing in addressing them. Particular attention will be given to plasma-based particle accelerators and the question of whether they really offer a path to smaller, cheaper accelerators that could impact human health through cancer therapies or enable new discoveries at the high energy frontier.

15:45

QR2 2 Gaseous Electronics Phenomena in Particle Accelerators*

SVETOZAR POPOVIC, *Old Dominion University, Physics Department, Center for Accelerator Science*

The work is motivated by the development of new compact superconducting RF (SRF) accelerating structures that are capable of producing gradients in excess of 100 MV/m. Compact accelerators and accelerator-based light sources are currently expected to have numerous applications ranging from use in medicine to high-energy physics. However, they require more compact accelerating cavities and components for beam control. Developing and operation of compact particle accelerators involve a multitude of concepts that are analogue to those developed in the traditional disciplines of gaseous electronics. Non-planar, asymmetric superconductor surface treatment using radiofrequency discharges applies techniques that are analogue to those used in the development of planar micro- and nano-electronic devices, although performed on much larger and curved surfaces. During operation, compact particle accelerators behave as pulsed power devices. Just as in the pulsed power devices, it has been reported that all compact concepts are inclined to support the field emission and the multipactor effects that, in turn, limit their range of operation. Multipactor discharge presents a major boulder in the development of compact accelerators and light sources. Multipactor is a resonant discharge generated by the RF field where the growth in the electron density is sustained by secondary emission from cavity walls driven by the RF power that is used for particle acceleration. If more than one electron is emitted for each primary electron, the rate of electron density growth could become high enough to dissipate a significant fraction of the RF power inside the cavity before the saturation due to space-charge or other effects sets in. Using the archived data collection on the performance tests of SRF accelerator components, we identify the relevant gaseous electronics phenomena and their mechanisms. We also review the efforts on mitigation of detrimental effects.

*Supported by DOE under Grant No. DE-SC0007879.

Contributed Papers

16:00

QR2 3 Uniform Plasma Etching of Complex Shaped Three Dimensional Niobium Structures for Particle Accelerators* JANARDAN UPADHYAY, DO IM, JEREMY PESHL, SVETOZAR POPOVIC, LEPSHA VUSKOVIC, *Old Dominion University* LARRY PHILLIPS, ANNE-MARIE VALENTE-FELLICIANO, *Jefferson Lab* Complex shaped three dimensional niobium structures are used in particle accelerators as super conducting radio frequency (SRF) cavities. The inner surfaces of these structures have to be chemically etched for better performance, as SRF performance parameters are very sensitive to their properties. Plasma etching of inner surface of three dimensional niobium structures has not been reported even though plasma etching of niobium has been reported earlier for Josephson junction and other applications. We are proposing an RF capacitively coupled coaxial (ccp) plasma etching method for nano machining of niobium structures for SRF applications. We are using gas mixture of Argon and Chlorine. We report the effects of the pressure, RF power, gas concentration, shape and size of the inner electrode, temperature of the structure, DC bias voltage and residence time on the etch rate of the niobium. We also show the method to reduce the asymmetry effect in coaxial ccp by changing the shape of the inner electrode in cylindrical structure, as well as a method to overcome the severe loading effect in etching of 3D structures for uniform mass removal purpose.

*Supported by DOE under Grant No. DE-SC0007879. J.U. acknowledges support by JSA/DOE via DE-AC05-06OR23177.

16:15

QR2 4 Plasma Studies in a High Pressure Gas Filled Radio Frequency Cavity BEN FREEMIRE, *Illinois Inst of Tech* MOSES CHUNG, ALVIN TOLLESTRUP, KATSUYA YONEHARA, *Fermi National Accelerator Laboratory* A Muon Collider offers a great deal of physics potential to the high energy physics community. In order to build such a machine with the desired luminosity, significant cooling of the muon beam is required. One proposed method for doing so is the Helical Cooling Channel, which consists of high pressure gas filled radio frequency (HPRF) cavities arranged in a helix within a strong external magnetic field. To validate this technology, an HPRF cavity was subjected to a 400 MeV proton beam at Fermilab's MuCool Test Area. Parent gases of hydrogen, deuterium, helium and nitrogen, at room temperature and densities up to 2.5E21 cm^{-3} were used, and doped with sulfur hexafluoride or dry air. The plasma density created by the beam approached 1E16 cm^{-3}. Measurements of the RF energy dissipated per charged particle pair, the electron-ion recombination rate, the ion-ion recombination rate, and electron attachment time were made.

SESSION QR3: COLLISIONS INVOLVING ANTIMATTER PARTICLES AND ATOMS

Thursday Afternoon, 6 November 2014; Room: State D at 15:30; Ugo Ancarani, Universite de Lorraine, presiding

Invited Papers

15:30

QR3 1 Positron Annihilation as a Probe of Intramolecular Vibrational Energy Redistribution (IVR)*

J. R. DANIELSON,† *University of California, San Diego*

Experiments at incident energies in the range of the molecular vibrations show that positrons can attach to molecules via vibrational Feshbach resonances [1]. While attached, the positron has an increased probability of annihilation, leading to an enhancement of the measured annihilation rate. This enhancement is limited because the vibrational auto-detachment rate is typically much faster than the annihilation time, meaning that most positrons escape before annihilating. However, in many molecules, intramolecular vibrational energy redistribution (IVR) couples the entrance mode energy into nearly isoenergetic multimode states. This process leads to either suppression or enhancement of the annihilation depending on whether the auto-detachment rate of the coupled vibrations is faster or slower than that of the entrance mode. These effects have recently been combined into a simplified rate-equation model which describes the effect of IVR on the measured annihilation rates [2]. With certain approximations, the primary unknown in the model is the IVR coupling rate. This model will be described and used to show how observations of annihilation enhancement or suppression can be used to extract an estimate of the IVR coupling rate for selected modes in several small molecules.

*This work was supported by NSF Grant PHY 10-68023.

†In collaboration with M. R. Natisin, A. C. L. Jones, and C. M. Surko.

[1]G. F. Gribakin *et al.*, Rev. Mod. Phys. **82**, 2557 (2010).
[2]J. R. Danielson *et al.*, Phys. Rev. A **88**, 062702 (2013).

Contributed Papers

16:00

QR3 2 Total cross sections for positron scattering from the noble gases ROBERT MCEACHRAN, *Australian National University* ALLAN STAUFFER, *York University* Our complex, relativistic optical potential method for the elastic scattering of electrons and positrons from atoms includes the effects of excitation and ionization of the target and thus produces elastic cross sections more accurately than using a purely real potential. We have used this method to calculate differential and integrated cross sections for scattering of electrons and positrons from the noble gases. Recently, we have included a simplified form of positronium formation in our formulation, resulting in very good agreement with experimental cross sections for positron scattering from the heavy noble gases at energies where positronium formation is important [1]. Since our method now produces results for total scattering cross sections (i.e. including contributions from elastic, excitation and ionization scattering as well as positronium formation) we can compare the results from our calculations with recent measurements of this quantity. Detailed comparisons will be made at energies above the positronium formation threshold which is the inelastic channel with the lowest energy threshold in positron scattering from the noble gases.

[1]R. P. McEachran and A. D. Stauffer, J. Phys. B **46**, 075203 (2013).

Invited Papers

16:15

QR3 3 Collisions and Transport in Antihydrogen Physics

MICHAEL CHARLTON, *Swansea University*

It has been possible for more than a decade to form antihydrogen atoms by the controlled mixing of antiprotons and positrons held in arrangements of charged particle traps [1]. More recently, magnetic minimum neutral atom traps have been superimposed upon the anti-atom production region, promoting the trapping of a small quantity of the antihydrogen yield [2–4] and first facilitating experiments [5]. We will describe some of the collision and plasma/transposrt physics that underpin these achievements, including a discussion of topical issues.

[1]see e.g., M. H. Holzscheiter, M. Charlton, and M. M. Nieto, Phys. Rep. **401**, 1 (2004), for a review.
[2]G. B. Andresen *et al.* (ALPHA Collaboration), Nature **468**, 673 (2010).
[3]G. B. Andresen *et al.* (ALPHA Collaboration), Nature Phys. **7**, 558 (2011).
[4]G. Gabrielse *et al.* (ATRAP Collaboration), Phys. Rev. Lett. **108**, 113002 (2012).
[5]C. Amole *et al.* (ALPHA Collaboration), Nature **483**, 439 (2012).

Contributed Papers

16:45

QR3 4 B-spline R-matrix with pseudostates calculations for electron collisions with atomic nitrogen* YANG WANG, *Harbin Institute of Technology* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* The *B*-spline *R*-matrix (BSR) with pseudostates method [1] is employed to treat electron collisions with nitrogen atoms. Predictions for elastic scattering, excitation, and ionization are presented for incident energies between threshold and about 100 eV. The largest scattering model included 690 coupled states, most of which were pseudostates that simulate the effect of the high-lying Rydberg spectrum and, most importantly, the ionization continuum on the results for transitions between the discrete physical states of interest. Similar to our recent work on e-C collisions [2], this effect is particularly strong at "intermediate" incident energies of a few times the ionization threshold. Predictions from a number of collision models will be compared with each other and the very limited information currently available in the literature. Estimates for ionization cross sections will also be provided.

*This work was supported by the China Scholarship Council (Y.W.) and the United States National Science Foundation under Grants PHY-1068140, PHY-1212450, and the XSEDE allocation PHY-090031 (O.Z. and K.B.).

[1]O. Zatsarinny and K. Bartschat, J. Phys. B **46**, 112001 (2013).
[2]Y. Wang, O. Zatsarinny, and K. Bartschat, Phys. Rev. A **87**, 012704 (2013).

17:00

QR3 5 Calculation of the polarization fraction and electron-impact excitation cross section for the $Cd^+(5p)^2P_{3/2}$ state* CHRISTOPHER J. BOSTOCK, DMITRY V. FURSA, IGOR BRAY, *Curtin University* KLAUS BARTSCHAT, *Drake University* We present fully relativistic convergent close-coupling and semirelativistic Breit-Pauli *R*-matrix calculations of the integrated cross section and the polarization fraction for electron-impact excitation of the $(5s)\,^2S_{1/2} \rightarrow (5p)\,^2P_{3/2}$ transition in Cd^+. Above 30 eV, the polarization fraction results are in agreement with earlier RDW calculations [1], but in disagreement with measurements [2], particularly above 60 eV. Cascade contributions and hyperfine depolarization are found to have a negligible affect on the polarization fraction but have a significant effect on the predicted cross section. We also find that the cross section over the entire energy range scales in proportion to the optical oscillator strength of the target model. This is an important generalization of Kim's f-scaling idea [3], since it does not require an ad-hoc shift of plane-wave Born results in the intermediate energy regime.

*Work supported by the Australian Research Council and the United States National Science Foundation.

[1]Sharma *et al.*, Phys. Rev. A **83**, 062701 (2011).
[2]Goto *et al.*, Phys. Rev. A **27**, 1844 (1983).
[3]Kim *et al.*, Phys. Rev. A **64**, 032713 (2001).

17:15

QR3 6 Effect of Charge Distribution in Out-of-Plane Structure for Excitation-Ionization Collisions A.L. HARRIS, T.P. ESPOSITO, *Illinois State University* We present fully differential cross sections (FDCS) for electron-impact excitation-ionization of helium when the ionized electron is found outside of the scattering plane. Using our 4-Body Distorted Wave and First Born Approximation models, we show that the shape of the FDCS is largely due to the charge distribution of the He+ ion in the final state. We also examine the effects of electron correlation in the target helium atom, and the effects of the projectile interactions with the target.

SESSION SF1: PLASMA SOURCES
Friday Morning, 7 November 2014; Room: State EF at 8:30; Julian Schulze, West Virginia University, presiding

Invited Papers

8:30

SF1 1 EED*f* and IED*f* of the non-ambipolar e$^-$-beam plasma and their effects on etch
LEE CHEN, *Tokyo Electron America, Inc.*

The control of electron shading is crucial in achieving the super-high aspect ratio contact (HARC); precise ion-energy control is essential in the selective etching of lamella diblock copolymers to develop the nano-lines for Direct Self Assembly (DSA). The plasma EED*f* not only determines the chemistry but also dictates the shading level of the features. The above processes are presented as examples to illustrate the effects of EED*f* and the surgical surface-excitation by a controlled IED*f*. In addition to demonstrating the methods of achieving a prescribed IED*f* through external bias, the properties of the non-ambipolar electron plasma (NEP) will be presented. NEP is heated by the non-ambipolar beam-current density in the range of 10s Acm^{-2} through beam-plasma instabilities. Its EED*f* has a Maxwellian bulk followed by a broad energy-continuum connecting to the most energetic group with energies above the beam-energy and such EED*f* seems consistent with that required for deep-contact etching. The remnant of the injected electron-beam power terminates at the NEP end-boundary (i.e., wafer) could set up a controllable DC sheath potential resulting in mono-energetic surface excitation by the charge-neutral plasma beam without the application of external bias. In collaboration with Zhiying Chen, Tokyo Electron America, Inc., Austin, TX 78741.

Contributed Papers

9:00

SF1 2 Two Different Plasma Series Resonances in a 100MHz Driven Narrow Gap Capacitively Coupled Plasma* MYUNG-SUN CHOI, SEOK-HWAN LEE, YUNCHANG JANG, SANG-WON RYU, *Seoul National University* SANGMIN JEONG, DOUGYONG SUNG, *Samsung Electronics* GON-HO KIM, *Seoul National University* Plasma series resonance (PSR) is the resonance between the sheath displacement and the inductance of plasma bulk. Especially, the linear response of this resonance is called "geometrical resonance" which is distinguished with the non-linear response of that called "self-excited PSR." In this work, geometrical series resonances of plasma slab in narrow gap ($d = 0.02m$) between the RF electrode ($r = 0.2m$) and floating electrode ($r = 0.15m$) encircled with the earthed chamber ($r = 0.3m$) were investigated with various applied 100 MHz powers from 100 W to 1 kW and operating pressures from 5 mTorr to 50 mTorr. The condition of plasma series resonance was monitored by using optical emission spectroscopy (OES) and amplitudes of current and voltage at the RF driven and counter electrodes. There were not only the plasma series resonance between the two parallel electrodes but also that between the RF driven electrode and the lateral wall of earthed chamber. Those two different plasma series resonances were observed alternatively with increasing applied power. In the session, the detailed analysis of alternatively arisen two different series resonances and influence of them on the discharge will be discussed.

*This work was partly supported by the Brain Korea 21 Plus Project (No. 21A20130012821).

9:15

SF1 3 Prevention of ion flux inhomogeneities in large area capacitively coupled discharges via the Electrical Asymmetry Effect* EDMUND SCHUENGEL, JULIAN SCHULZE, *Department of Physics, West Virginia University, Morgantown, WV 26506* SEBASTIAN MOHR, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum, 44780 Bochum, Germany* For large area processing applications of capacitively coupled radio frequency (CCRF) discharges, the lateral uniformity of the plasma surface interaction is crucially important. The benefit of an increase in the plasma density and, therefore, in the overall deposition rate by driving the discharge at higher frequencies is accompanied with inhomogeneities caused by the presence of electromagnetic effects. Here, we propose a method based on the Electrical Asymmetry Effect (EAE) to prevent such inhomogeneities. Spatially resolved measurements of the ion flux onto the grounded electrode of a CCRF discharge operated in hydrogen show a standing wave pattern in a 81.36 MHz single-frequency discharge, strongly reducing the ion flux uniformity. However, applying a dual-frequency voltage waveform consisting of 40.68 MHz + 81.36 MHz, the lateral distribution of the ion flux can be controlled via the phase angle between the two applied harmonics. Using the EAE, a phase angle dependent DC self-bias develops in the geometrically symmetric discharge. Tuning the phase angle allows for the compensation of ion flux inhomogeneities due to the standing wave effect. Thus, a high and laterally uniform ion flux can be generated in electrically asymmetric high frequency plasmas.

*Funding by the German Federal Ministry for the Environment, Nature conservation, and Nuclear Safety (0325210B) is gratefully acknowledged.

9:30

SF1 4 Transient response of pulsed multi-source RF CCP discharges* THERESA KUMMERER, DAVID PETERSON, *North Carolina State University* DAVID COUMOU, *MKS Instruments* STEVEN SHANNON, *North Carolina State University* The electrical response of a pulsed RF CCP discharge with a second CW power source is studied within the kHz timescale of a typical pulsed system. This response is compared to plasma parameters such as sheath thickness, electron density, electron temperature, and optical emission to elucidate trends with respect to operating condition. Several regions within the pulse cycle with characteristic decay constants and saturation points have been identified using voltage, current, and phase measurements from the CW powered electrode. These trends are compared to global plasma parameters measured using Langmuir probe, hairpin resonators, spectroscopy, and high time resolution in-line RF metrology. These observed transient regions have a dependence on pressure, relative power levels, pulse frequency, and gas composition. Data was taken using argon and argon-oxygen plasmas with pulsing plurality of frequency configurations where one generator is pulsed while the other maintains constant power output. The goal of this study is to parameterize conditions for active power delivery control in advanced multi-source RF systems that utilize pulsing on one or more of their power supplies.

*Work supported through the NSF/DOE partnership in Basic Plasma Science and NSF IIP GOALI Program (Grant 1202259).

9:45

SF1 5 Etching of photoresist with an atmospheric pressure plasma jet* ANDREW WEST, *York Plasma Institute, University of York, UK* MARC VAN DER SCHANS, *Eindhoven University of Technology, The Netherlands* CIGANG XU, *Oxford Instruments Plasma Technology, UK* TIMO GANS, *York Plasma Institute, University of York, UK* MIKE COOKE, *Oxford Instruments Plasma Technology, UK* ERIK WAGENAARS, *York Plasma Institute, University of York, UK* Low-pressure oxygen plasmas are commonly used in semiconductor industry for removing photoresist from the surface of processed wafers; a process known as plasma ashing or plasma stripping. The possible use of atmospheric-pressure plasmas instead of low-pressure ones for plasma ashing is attractive from the point of view of reduction in equipment costs and processing time. We present investigations of photoresist etching with an atmospheric-pressure plasma jet (APPJ) in helium gas with oxygen admixtures driven by radio-frequency power. In these experiments, the neutral, radical rich effluent of the APPJ is used for etching, avoiding direct contact between the active plasma and the sensitive wafer, while maintaining a high etch rate. Photoresist etch rates and etch quality are measured for a range of plasma operating parameters such as power input, driving frequency, flow rate and wafer temperature. Etch rates of up to 10 micron/min were achieved with modest input power (45 W) and gas flow rate (10 slm). Fourier Transform Infrared (FTIR) spectroscopy showed that the quality of the photoresist removal was comparable to traditional plasma ashing techniques.

*This work was supported by the UK Engineering and Physical Sciences Research Council Grant EP/K018388/1.

10:00

SF1 6 Development and characterization of a fast neutral beam source for damage-free etching* MARK BOWDEN, *University of Liverpool* DANIIL MARINOV, ADETOKUNBO AYILARAN, NICHOLAS BRAITHWAITE, *The Open University* ZIAD EL OTELL, *IMEC* Etching with energetic neutral beams is a promising technology for next generation sub-10 nm device fabrication. In this study a fast neutral beam has been produced by accelerating, extracting and neutralizing positive and negative ions from different phases of a pulsed discharge. A cylindrical, inductively coupled plasma (ICP) was excited between two planar disk-electrodes in mixtures of SF_6 and O_2 at about 20 mTorr. The discharge was pulsed at 2 kHz and 50% duty cycle. The extraction electrode was a 10 mm thick carbon plate (or a 0.8 mm steel plate) with an array of 1 mm holes, held at ground potential. Ions grazing the sides of the extraction holes incidence have a high probability (70–95%) of neutralization. The other electrode was pulse-biased to extract negative or positive ions during the afterglow phase, after an ion-ion plasma had formed. The total flux and velocity distribution of extracted ions was measured using a retarding field analyser. Extraction of mono-energetic positive and negative ion beams with energies in the range 10–300 eV was demonstrated. It was shown that the beam energy can be precisely controlled by the bias waveform tailoring and by positioning of the extraction electrodes.

*We acknowledge support from the European Union under Grant Agreement No. 318804 (SNM).

10:15

SF1 7 Hysteresis in Radio-Frequency Inductively Coupled Plasmas HYO-CHANG LEE, CHIN-WOOK CHUNG, *Hanyang University* We present both experimental and theoretical studies of hysteresis in radio-frequency inductive discharges. It is found that the hysteresis is significantly affected by nonlinearity of the plasma with the modification of electron energy distribution (EED). This kind of hysteresis is also observed in various plasma discharges with powers, pressures, and magnetic field where EEDs are evolved.

SESSION SF2: THERMAL AND MICROWAVE PLASMAS

Friday Morning, 7 November 2014
Room: State C at 8:30
Venkatt Ayyaswamy, University of California Merced, presiding

Contributed Papers

8:30

SF2 1 Experimental Characterization of Magnetogasdynamic Phenomena in Ultra-High Velocity Pulsed Plasma Jets* KEITH LOEBNER, BENJAMIN WANG, MARK CAPPELLI, *Stanford University* The formation and propagation of high velocity plasma jets in a pulsed, coaxial, deflagration-type discharge is examined experimentally. A sensitive, miniaturized, immersed probe array is used to map out magnetic flux density and associated radial current density as a function of time and axial position. This array is also used to probe the magnetic field gradient across the exit of the accelerator and in the jet formation region. Sensitive interferometry via a continuous-wave helium-neon laser source is used to probe the structure of the plasma jet over multiple chords and axial locations. A two dimensional plasma density gradient profile at an instant in time during jet formation is compiled via Shack-Hartmann wavefront sensor analysis. The qualitative characteristics of rarefaction and/or shock wave formation as a function of chamber back-pressure is examined via fast-framing ICCD imaging. These measurements are compared to existing resistive MHD simulations of the coaxial deflagration accelerator and the ensuing rarefaction jet that is expelled from the electrode assembly. The physical mechanisms governing the behavior of the discharge and the formation of these high energy density plasma jets are proposed and validated against both theoretical models and numerically simulated behavior.

*This research was conducted with Government support under and awarded by DoD, Air Force Office of Scientific Research, National Defense Science and Engineering Graduate (NDSEG) Fellowship, 32 CFR 168a.

8:45

SF2 2 Plasma diagnostics of non-equilibrium atmospheric plasma jets ALEXEY SHASHURIN, DAVID SCOTT, MICHAEL KEIDAR, *The George Washington University* MIKHAIL SHNEIDER, *Princeton University* Intensive development and biomedical application of non-equilibrium atmospheric plasma jet (NEAPJ) facilitates rapid growth of the plasma medicine field. The NEAPJ facility utilized at the George Washington University (GWU) demonstrated efficacy for treatment of various cancer types (lung, bladder, breast, head, neck, brain and skin). In this work we review recent advances of the research conducted at GWU concerned with the development of NEAPJ diagnostics including Rayleigh Microwave Scattering setup, method of streamer scattering on DC potential, Rogowski coils, ICCD camera and optical emission spectroscopy. These tools allow conducting temporally-resolved measurements of plasma density, electrical potential, charge and size of the streamer head, electrical currents flowing though the jet, ionization front propagation speed etc. Transient dynamics of plasma and discharge parameters will be considered and physical processes involved in the discharge will be analyzed including streamer breakdown, electrical coupling of the streamer tip with discharge electrodes, factors determining NEAPJ length, cross-sectional shape and propagation path etc.

Invited Papers

9:00

SF2 3 Dynamic Contraction of the Positive Column of a Self-Sustained Glow Discharge in Molecular Gas Flow
MIKHAIL SHNEIDER, *Princeton University*

Contraction of the gas discharge, when current contracts from a significant volume of weakly ionized plasma into a thin arc channel, was attracted attention of scientists for more than a century. Studies of the contraction (also called constriction) mechanisms, besides carrying interesting science, are of practical importance, especially when contraction should be prevented. A set of time-dependent two-dimensional equations for the non-equilibrium weakly-ionized nitrogen/air plasma is formulated. The process is described by a set of time-dependent continuity equations for the electrons, positive and negative ions; gas and vibrational temperature; by taking into account the convective heat and plasma losses by the transverse flux. Transition from the uniform to contracted state was analyzed. It was shown that such transition experiences a hysteresis, and that the critical current of the transition increases when the pressure (gas density) drops. Possible coexistence of the contracted and uniform state of the plasma in the discharge where the current flows along the density gradient of the background gas was discussed. In this talk the problems related to the dynamic contraction of the current channel inside a quasineutral positive column of a self-sustained glow discharge in molecular gas in a rectangular duct with convection cooling will be discussed. Study presented in this talk was stimulated by the fact that there are large number of experiments on the dynamic contraction of a glow discharge in nitrogen and air flows and a many of possible applications. Similar processes play a role in the powerful gas-discharge lasers. In addition, the problem of dynamic contraction in the large volume of non-equilibrium weakly ionized plasma is closely related to the problem of streamer to leader transitions in lightning and blue jets.

[1]M. N. Shneider, M. S. Mokrov, and G. M. Milikh, Phys. Plasmas **19**, 033512 (2012).
[2]M. N. Shneider, M. S. Mokrov, and G. M. Milikh, Phys. Plasmas **21**, 032122 (2014).
[3]G. M. Milikh, M. N. Shneider, and M. S. Mokrov, JGR (2014) (submitted).

Contributed Papers

9:30

SF2 4 Pulsed laser measurement of temperature and conductivity of a decaying arc channel PATRICK STOLLER, EMMANOUIL PANOUSIS, JAN CARSTENSEN, VALERIA TEPPATI, *ABB Switzerland Ltd.* When a high voltage circuit breaker interrupts alternating current, the arc established between its contacts is axially blown by a transonic gas flow until it is extinguished at a current-zero crossing. Improvement of circuit breaker design to achieve higher short circuit current ratings or more compact equipment relies on an understanding of the processes involved in cooling and interruption of the arc. At present, current, voltage, and pressure measurements together with CFD simulations give only limited insight into how the arc is cooled—mainly via convection and radiation—and finally is interrupted via turbulent mixing. Measurement of the density, temperature, and conductivity of the arc embedded in a gas-flow would permit validation of the CFD simulations and allow direct quantitative determination of important parameters such as the arc and boundary layer width and temperature. We have developed a Speckle imaging technique that permits determination of these parameters via measurement of the refractive index. A pulsed, nanosecond laser is used to interrogate the arc and surrounding flow. The short pulse length permits visualization of turbulent flow features and prevents smearing of time varying features of the flow and the arc that may occur if a continuous wave laser is used. We present and compare to CFD simulations measurements of the temperature, density, and conductivity of axially blown arcs. Based on these results we examine the dependence of the arc width on blowing conditions.

9:45

SF2 5 Pseudo-continuous meter-scale microwave plasma production under atmospheric pressure HIROTAKA TOYODA, HARUKA SUZUKI, SUGURU NAKANO, *Nagoya University* HITOSHI ITOH, *Tokyo Electron Ltd* MAKOTO SEKINE, MASARU HORI, *Nagoya University* Atmospheric pressure plasmas (APP) have been given much attention because of its cost benefit and a variety of possibilities for industrial applications such as large area processing. We have been studying production of a pseudo-continuous meter-scale 2.45 GHz microwave APP source which consists of a loop-structure waveguide antenna and a circulator. Plasma is produced inside a meter-length slot of the waveguide and pseudo-continuous plasma is realized by fast movement of small (a few mm in length) plasmas along the slot. In this study, plasma behavior is investigated by a high-speed camera and an ICCD camera to give insight into the mechanism of the plasma movement. In emission intensity profile along the slot from a single plasma, asymmetric structure and higher emission intensity was observed in the vicinity of the plasma edge of the microwave downstream side, suggesting the plasma movement was induced by the asymmetric ionization rate in the single plasma. Origin of such asymmetric structure was investigated using a simulation of three-dimensional electromagnetic field.

10:00

SF2 6 CO_2 dissociation in vortex-stabilised microwave plasmas

S. WELZEL,* W.A. BONGERS, M.F. GRASWINCKEL, M.C.M. VAN DE SANDEN,† *FOM Institute DIFFER, Edisonbaan 14, 3439 MN Nieuwegein* Plasma-assisted gas conversion techniques are widely considered as efficient building blocks in a future energy infrastructure which will be based on intermittent, renewable electricity sources. CO_2 dissociation in high-frequency plasmas is of particular interest in carbon capture and utilisation process chains for the production of CO_2-neutral fuels. In order to achieve efficient plasma processes of high throughput specifically designed gas flow and power injection regimes are required. In this contribution vortex-stabilised microwave plasmas in undiluted CO_2 were studied in a pressure range from 170 to 1000 mbar at up to 1 kW (forward) injected power, respectively. The CO_2 depletion was measured downstream, e.g. by means of mass spectrometry. Although the system configuration was entirely not optimised, energy efficiencies of nearly 40%, i.e. close to the thermal dissociation limit, and conversion efficiencies of up to 23% were achieved. Additionally, spatially-resolved emission spectroscopy was applied to map the axial and radial distribution of excited atomic (C, O) and molecular (CO, C_2) species along with their rotational temperatures.

*Eindhoven University of Technology, Postbox 513, 5600 MB Eindhoven.

†Eindhoven University of Technology, Postbox 513, 5600 MB Eindhoven.

10:15

SF2 7 Experimental observation of electron density bifurcation in plasma-metamaterial composites in microwave range

OSAMU SAKAI, YOSHIHIRO NAKAMURA, AKINORI IWAI, *Kyoto University* Metamaterials, which are composed of designed microstructures and show extraordinary electromagnetic responses, match plasmas so well, and high-power microwaves induce bifurcation phenomena in this plasma-metamaterial composite. Since dielectric constant or permittivity of plasmas varies from positive to negative values at microwave frequencies, the composite with negative permeability becomes a reconfigurable negative refractive index material [1]. Furthermore, as indicated by our recent report [2,3], this composite shows strong nonlinear properties. Bifurcation of permittivity (or electron density) was predicted by a theory [2], and we have verified it in our recent experiments; using double split ring resonators whose array showed negative permeability at 2.45 GHz, clear bifurcation with hysteresis was observed in electron density evolutions with input power $\leq$300 W. This result implies that this composite is a nonlinear microwave metamaterial.

[1] O. Sakai *et al.*, Plasma Sources Sci. Technol. **13**, 013001 (2013).

[2] O. Sakai, J. Appl. Phys. **109**, 084914 (2011).

[3] Y. Nakamura and O. Sakai, Jpn. J. Appl. Phys. **53**, 03DB04 (2014).

SESSION SF3: ELECTRON COLLISIONS WITH ATOMS AND MOLECULES

Friday Morning, 7 November 2014; Room: State D at 8:30; Allan Stauffer, York University, presiding

Invited Papers

8:30

SF3 1 Angular distributions for ionization from excited states of atoms*

JAMES COLGAN, *Los Alamos National Laboratory*

We present recent theoretical work examining cross sections for electron-impact ionization of excited states of atoms. Our work is motivated by recent measurements of the angular differential cross sections from electron-impact single ionization of Mg atoms in the $3s3p$ excited state [1], which were prepared by laser excitation of the Mg target. We use the time-dependent close-coupling approach to electron-impact ionization [2] and explore the angular distributions from excited state Na and Mg, building on recent work by us in which we examined the angular distributions from the ground states of Na and Mg [3]. We examine the differences between the angular distributions resulting from ionization of the ground and excited states. Our calculations are also compared to the recent measurements [1], and we highlight where further work would be desirable in this area.

*The Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. DE-AC5206NA25396.

[1] K. L. Nixon and A. J. Murray, Phys. Rev. Lett. **106**, 123201 (2011); **112**, 023202 (2014).

[2] J. Colgan and M. S. Pindzola, Eur. J. Phys. D **66**, 284 (2012).

[3] G. S. J. Armstrong, J. Colgan, and M. S. Pindzola, Phys. Rev. A **88**, 042713 (2013).

Contributed Papers

9:00

SF3 2 Theoretical and experimental results for electron-impact ionization of the 3p state of Mg that has been laser aligned*

SADEK AMAMI, DON MADISON, *Missouri Univ of Sci & Tech* KATE NIXON, ANDREW MURRAY, *University of Manchester, Manchester, United Kingdom* JAMES COLGAN, *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA* Low energy theoretical and experimental quadruple differential cross sections (QDCS) will be presented for electron impact ionization of magnesium atoms that have been aligned by lasers. The incident projectile electron has an energy of 43.31 eV, the scattered and ejected electrons were detected with equal energies (E1 = E2 = 20 eV), one of the final state electrons was detected at a fixed scattering angle of 30 degrees, and the other final state electron is detected at angles ranging between 0 degrees and 180 degrees. The Mg atoms are excited to the 3p state using a linearly polarized laser which produces a standing wave aligned perpendicular to the laser beam direction. Theoretical results will be compared with the experimental data for several different alignment angles both in the scattering plane as well as in the plane perpendicular to the incident beam direction.

*This work is supported by the US National Science Foundation under Grant. No. PHY-1068237.

9:15

SF3 3 Quasi-Sturmian basis functions for two- and three-body scattering problems. JESSICA A. DEL PUNTA, LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* GUSTAVO GASANEO, *Universidad Nacional del Sur, Bahia Blanca, Argentina* For quantum three-body scattering processes, one important theoretical issue is how to impose to the wave function the correct asymptotic behavior. In many methods the problem is solved using basis functions that generally do not possess the correct behavior at large distances. One exception is given by the Generalized Sturmian Functions (GSF) [1] which are defined taking into account the interactions of the problem under consideration, thus making them an efficient basis set. We present in this work an alternative set of basis functions, named Quasi Sturmian Functions (QSF). Starting with the two-body case [2], QSF satisfy a non-homogeneous differential equation, and may be constructed with a selected asymptotic behavior (e.g. outgoing). Contrary to GSF, these basis functions have analytical closed form for the case of a Coulomb potential. Moreover, we showed that the QSF provide a superior convergency rate when solving a two-body scattering problem. For the three-body case, we propose a representation using hyperspherical coordinates. While the angular variables are treated in a parametric way, the hyperradial part of these new QSF basis functions are obtained by a generalization of the method used for the two-body problem. As a consequence, analytical expressions can be given for these new QSF and the desired Coulomb asymptotic behavior in the hyperradial coordinate can be imposed.

[1]G. Gasaneo *et al.*, Adv. Quantum Chem. **67**, 153 (2013).
[2]J. A. Del Punta *et al.*, J. Math. Phys. **55**, 052101 (2014).

Invited Papers

9:30

SF3 4 Low energy electron-molecule scattering using the R-matrix method*
JIMENA GORFINKIEL, *The Open University*

The study of electron-molecule collisions continues to attract significant interest stimulated, in no small part, by the need for collisional data to model a number of physical environments and applied processes (e.g. the modelling of focused electron beam induced deposition and the description of the interaction of radiation with biological matter). This need for electron scattering data (cross sections but also information on the temporary negative ions, TNI, that can be formed) has motivated the renewed development of theoretical methodology and their computational implementation. I will present the latest developments in the study of low energy electron scattering from molecules and molecular clusters using the R-matrix method. Recent calculations on electron collisions with biologically relevant molecules have shed light on the formation of core-excited TNI these larger targets. The picture that emerges is much more complex than previously thought. I will discuss some examples as well as current and future developments of the methodology and software in order to provide more accurate collisional data (in particular cross sections) for bigger targets. In collaboration with Zdenek Masin, The Open University.

*This work was partially supported by EPSRC.

Contributed Papers

10:00

SF3 5 Theoretical and Experimental Triple Differential Cross Sections for Electron Impact Ionization of SF_6* HARI CHALUVADI, *Missouri University of Science and Technology* KATE NIXON, ANDREW MURRAY, *University of Manchester* CHUANGANG NING, *Tsinghua University* JAMES COLGAN, *Los Alamos National Laboratory* DON MADISON, *Missouri University of Science and Technology* Experimental and theoretical Triply Differential Cross Sections (TDCS) will be presented for electron-impact ionization of sulfur hexafluoride (SF6) for the molecular orbital 1t1g. M3DW (molecular 3-body distorted wave) results will be compared with experiment for coplanar geometry and for perpendicular plane geometry (a plane which is perpendicular to the incident beam direction). In both cases, the final state electron energies and observation angles are symmetric and the final state electron energies range from 5 eV to 40 eV. It will be shown that there is a large difference between using the OAMO (orientation averaged molecular orbital) approximation and the proper average over all orientations and also that the proper averaged results are in much better agreement with experiment.

*Work supported by NSF under Grant Number PHY-1068237. Computational work was performed with Institutional resources made available through Los Alamos National Laboratory.

10:15

SF3 6 Importance of projectile-target interactions in the triple differential cross sections for Low energy (e,2e) ionization of aligned H_2 ESAM ALI, DON MADISON, *Missouri Univ of Sci & Tech* X. REN, A. DORN, *Max-Plank-Institute for Nuclear Physics* CHUANGANG NING, *Tsinghua University, Beijing, China* Experimental and theoretical Triple Differential Cross Sections (TDCS) are presented for electron impact ionization-excitation of the $2s\sigma_g$ state of H_2 in the perpendicular plane. The excited $2s\sigma_g$ state immediately dissociates and the alignment of the molecule is determined by detecting one of the fragments. Results are presented for three different alignments in the xy-plane (scattering plane is xz)-alignment along y-axis, x-axis, and 45°

between the *x*- and *y*-axes for incident electron energies of 4, 10, and 25 eV and different scattered electron angles of 20° and 30° in the perpendicular plane. Theoretical M4DW (molecular 4-body distorted wave) results are compared to experimental data, and overall we found reasonably good agreement between experiment and theory. The Results show that (e,2e) cross sections for excitation-ionization depend strongly on the orientation of the H_2 molecule.

A

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NOTES

Epitome of the 2014 Annual Fall Meeting of the Gaseous Electronics Conference

08:00 MONDAY MORNING
03 NOVEMBER 2014

AM1 **Advanced RF Systems for Plasma Control**
David Coumou
Room: State EF

AM2 **Workshop: Plasma Verification and Validation**
J.P. Verboncoeur, Andrew Christlieb, Miles Turner, L.C. Pitchford, Keigh Cartwright, Christopher Roy, William Rider
Room: State C

08:00 TUESDAY MORNING
04 NOVEMBER 2014

CT1 **Plasma Boundaries, Sheaths, and Basic Plasma Physics I**
Scott D. Baalrud
Room: Ballroom EF

CT2 **Propulsion and Aerodynamics**
Amnon Fruchtman, Ane Aanesland
Room: State C

CT3 **Plasma Chemistry**
Room: State D

10:00 TUESDAY MORNING
04 NOVEMBER 2014

DT1 **Plasma Diagnostics I**
John B. Boffard
Room: State EF

DT2 **Plasma Modeling and Simulations I**
Room: State C

DT3 **Effects of Plasmas on Biological Cells**
Nevena Puac, Toshiro Kaneko
Room: State D

13:30 TUESDAY AFTERNOON
04 NOVEMBER 2014

ET1 **Plasma Diagnostics and Sources for Biological Applications**
Room: State EF

ET2 **Modeling of Plasma Etching**
Koji Eriguchi
Room: State C

ET3 **Dielectric Barrier Discharges and Corona**
Jose L. Lopez
Room: State D

15:30 TUESDAY AFTERNOON
04 NOVEMBER 2014

FT1 **Plasma Surface Interactions**
Scott Kovaleski
Room: State EF

FT2 **Capacitive Discharges - Computational**
Kallol Bera
Room: State C

FT3 **Graphene Synthesis; Plasma Light Generation**
Room: State C

17:30 TUESDAY EVENING
04 NOVEMBER 2014

GT1 **Poster Session I (17:30-19:30)**
Exhibit Hall

08:00 WEDNESDAY MORNING
05 NOVEMBER 2014

HW1 **Non-equilibrium Kinetics and Basic Plasma Physics of Low Temperature Plasmas**
Room: Ballroom EF

HW2 **Dusty Plasmas and Negative Ions**
Room: State C

HW3 **Plasma Interactions with Biological Surfaces**
Michael Kong
Room: State D

10:00 WEDNESDAY MORNING
05 NOVEMBER 2014

JW1 **The Will Allis Prize for the Study of Ionized Gases**
David Graves
Room: State EF

11:00 WEDNESDAY MORNING
05 NOVEMBER 2014

JW2 **GEC Business Meeting**
Room: State AB

13:30 WEDNESDAY AFTERNOON
05 NOVEMBER 2014

KW1 **Plasma Diagnostics II**
Kenji Ishikawa
Room: State EF

KW2 **Reactive Microdischarges**
Room: State C

KW3 **Electron-Molecule Collisions and Related Processes I**
Nicholas Shuman, Darryl Jones
Room: State D

15:30 WEDNESDAY AFTERNOON
05 NOVEMBER 2014

LW1 **Plasma Diagnostics III**
Room: State EF

LW2 **Plasmas in Liquids**
Room: State C

LW3 **Electron-Molecule Collisions and Related Processes II**
Sylwia Ptasinska, Daniel Slaughter
Room: State D

17:30 WEDNESDAY EVENING
05 NOVEMBER 2014

MW1 **Poster Session II (17:30-19:30)**
Exhibit Hall

08:00 THURSDAY MORNING
06 NOVEMBER 2014

MR2 **Plasma Interactions with Liquid**
David B. Go, Paul Rumbach, David Bartels, R. Mohan Sankaran, Mark Kushner, Peter Bruggerman, Zachary Taillefer, John Blandin, James Szabo
Room: State C

MR3 **Plasma Enhanced Chemically Reactive Flows**
Igor V. Adamovich, Walter R. Lempert, Sergey Lenonov, Andrey Starikovskiy, Hyungrok Do, Campbell D. Carter
Room: State D

10:00 THURSDAY MORNING
06 NOVEMBER 2014

NR1 **Plasma Boundaries, Sheaths, and Basic Plasma Physics II**
Scott Robertson, J. P. Sheehan
Room: State EF

NR2 **Magnetically Enhanced Plasmas**
Andrei Smolyakov, John Forster
Room: State C

NR3 **Heavy Particle Collisions**
Alisher Kadyrov, Sebastian Otranto
Room: State D

13:30 THURSDAY AFTERNOON
06 NOVEMBER 2014

PR1 **Microdischarge Devices**
Room: State EF

PR2 **Plasma Deposition and Nanoparticle Generation**
Rebecca Anthony
Room: State C

PR3 **Coronal and HV Discharges**
Room: State D

15:30 THURSDAY AFTERNOON
06 NOVEMBER 2014

QR1 **Plasma Modeling and Simulations II**
Room: State EF

QR2 **Plasma Applications in Accelerator Technology**
Thomas Katsouleas, Svetozar Popovic
Room: State D

QR3 **Collisions Involving Antimatter Particles and Atoms**
J. R. Danielson, Michael Charlton
Room: State D

08:30 FRIDAY MORNING
07 NOVEMBER 2014

SF1 **Plasma Sources**
Lee Chen
Room: State EF

SF2 **Thermal and Microwave Plasmas**
Mikhail Shneider
Room: State C

SF3 **Electron Collisions with Atoms and Molecules**
James Colgan, Jimena Gorfinkiel
Room: State D

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