Tuesday Morning, November 8, 2016

Plasma Science and Technology
Room 104B - Session PS-TuM

Plasma Diagnostics, Sensors and Control

Moderator: Michael Gordon, University of California at Santa Barbara

8:00am **PS-TuM1 Translational and Vibrational Energy in Cl_2 and O_2 Plasmas Probed by Innovative Optical Diagnostics***, **Jean-Paul Booth**, D. Marinov, M. Foucher, O.Y.N. Guaitella,* LPP-CNRS, Ecole Polytechnique, France*; C. Drag,* Laboratoire Aime Cotton, CNRS-U. Paris-Sud, France*; A. Agarwal, S. Rauf,* Applied Materials Inc. **INVITED**

A common assumption for "Low-temperature" plasmas is that neutral molecules and atoms in the system are in thermal equilibrium with the surrounding ambient (room) temperature, and only charged particles, which can acquire energy from applied electric fields, have higher mean energies. In reality, energy can be transferred from electrons or ions to the neutral gas, increasing the gas translational temperature. Furthermore, non-equilibrium vibrational or rotational distributions can occur in molecular gas plasmas. This can have significant effects on the plasma dynamics. Firstly, since most plasma reactors operate in a pressure-controlled regime, high gas temperatures will cause a considerable decrease in gas density (and therefore in electron-neutral collision rates). Secondly, the rates of activated processes may be significantly increased by translational energy. Vibrational excitation can lead to large increases in the rates of electron dissociative attachment and neutral dissociation. We have developed a new, unambiguous technique to measure gas translational temperature of atoms, using Doppler-resolution Two-Photon Absorption Laser Induced Fluorescence (HR-TALIF) employing a specially-built narrow-bandwidth tuneable pulsed UV laser. Initial results have been obtained on oxygen atoms, where a measurement precision of ±10K is readily obtained. In a DC glow discharge in pure O_2 the gas temperature up to 550K are observed. The technique will be extended to the study of lower-pressure inductively-coupled plasmas, where higher temperatures are expected, and to chlorine atoms.

In order to investigate vibrational distributions, we have developed a high-sensitivity ultra-broadband ultraviolet absorption spectrometer. This employs a highly-stable laser-plasma light source and achromatic optics, allowing absorption spectra over a 250nm range to be measured with a baseline stability of the order 10^{-5}. In pure O_2 discharges (both DC glow and in a low-pressure ICP reactor) we were able to observe oxygen molecules in vibrationally-excited levels up to v=18 (more than half-way to dissociation), with a "tail" vibrational temperature of 7000K. Vibrational excitation was also detected in Cl_2 molecules in a pure Cl_2 ICP. However, Cl_2 appears to be close to thermal equilibrium with the gas translational temperature, which nevertheless approaches 2000K in this case.

This work was performed within the LABEX Plas@par project, and received financial state aid managed by the Agence Nationale de la Recherche, as part of the programme "Investissements d'avenir" under the reference ANR-11-IDEX-0004-02 and ANR project CleanGRAPH ((ANR-13-BS09-0019).It was also supported by the Applied Materials University Research Partnership Program

8:40am **PS-TuM3 Spectroscopic Measurement of Molecular Densities and Temperatures in Processing Plasmas***, **Yaser Helal**[*], C.F. Neese, F.C. De Lucia,* The Ohio State University*; A. Agarwal, B. Craver, P.R. Ewing, P.J. Stout, M.D. Armacost,* Applied Materials, Inc.

Processing plasmas are of a similar pressure and temperature to the environment used to study astrophysical species in the submillimeter/terahertz spectral region. Many of the molecular neutrals, radicals, and ions present in processing plasmas have been studied in the laboratory and their absorption spectra have been cataloged or are in the literature for the purpose of astrophysical study. Thus, the methods developed over several decades in the submillimeter spectral region for these laboratory studies are directly applicable for use in the semiconductor manufacturing industry. In this work, a continuous wave submillimeter absorption spectrometer was developed to study its viability as a remote sensor of gas and plasma species. A major advantage of intensity calibrated rotational absorption spectroscopy is that it can be used to determine absolute concentrations and temperatures of plasmas species from first principles without altering the plasma environment. An important part of this work was the design of the optical components which manage the coupling of the 500 – 750 GHz radiation through a commercial inductively coupled plasma (ICP) etch chamber using its existing viewport. A software routine was developed to simultaneously fit for background and absorption signal. The absorption signal determines the concentration, rotational temperature, and translational temperature of polar species. Examples of measurements made in ICPs will be demonstrated.

9:20am **PS-TuM5 Pulsed Capacitively Coupled Plasma Ignition: PROES and RF-IV Diagnostics***, **John Poulose**, M.J. Goeckner, L.J. Overzet,* The University of Texas at Dallas

Pulsed plasma ignition induces rapid changes to the electron energy distribution function. These transitions are of particular interest in the application of etching and deposition of semiconductors. In this article we report temporally and

spatially resolved measurements of the optical emission intensity and RF current and voltage for 1 kHz pulsed plasmas in both electropositive (Ar) and electronegative (CF4=O2=Ar) gas mixtures. This allows us to develop a better understanding of the transients during the beginning and end of the powered component of the RF pulse. We are able show the development of the plasma sheath early in the pulse by combining phase resolved optical emission intensity measurements with measurements of the radio frequency power delivery. In the electronegative discharge we find that the sheath width is minuscule early in the pulse but then expands rapidly. The rapid expansion results in a wave like phenomenon with negative ions bouncing between the growing sheaths.

9:40am **PS-TuM6 Control of Ion Energy Distributions on Insulating Surfaces using Pulsed Plasmas***, **Tyler List**, T. Mu, V.M. Donnelly, D.J. Economou,* University of Houston

As the requirements for plasma etching become more stringent, the need for plasmas that can produce monoenergetic ion energy distributions (IED) keeps increasing. The problem of charging inside of insulating features also becomes magnified at smaller feature sizes, which result in higher aspect ratios. A process in which electrons can reach and neutralize charged features is important to creating nearly monoenergetic IEDs. An argon RF pulsed plasma with synchronous DC boundary voltage was used to generate a nearly monoenergetic IED. To minimize charging of insulating surfaces, short positive voltage pulses were applied to the chuck holding the substrate during the afterglow, capacitively-coupling to the substrate surface and causing electrons to reach the surface and neutralize the surface charge. This allows a self-limited, nearly grounded surface potential to be achieved. Consequently, positive ions can reach the surface without slowing down by positive surface charge. The ion energy therefore is equal to and controlled by the plasma potential relative to ground, set by a synchronous bias voltage in the afterglow of the pulsed plasma. Surface potential measurements confirmed that DC chuck pulses temporarily neutralize the surface charge. Retarding field energy analyzer measurements performed on the floating chuck with the pulsed plasma and no boundary bias or chuck bias pulses showed an IED with a large very low energy peak (~0-2 eV) and a low energy peak (~10 eV, depending on pressure), corresponding to the power off and power on portions of the cycle, respectively. When the boundary bias and chuck pulses are applied in the afterglow, these peaks change slightly and a third peak appears at an energy near that of the boundary bias voltage. Analysis of the passive charging rate on the surface allowed the prediction of optimal pulsing frequency. Careful tuning of the other chuck pulsing width and amplitude, as well as the pulsed plasma parameters, also improves control of the IED.

11:00am **PS-TuM10 Charged Particle Dynamics in Technological Radio Frequency Plasmas Operated in CF_4***, **Julian Schulze**,* West Virginia University*; B. Berger,* Ruhr-University Bochum, Germany*; S. Brandt,* West Virginia University*; B. Bruneau,* Ecole Polytechnique, Palaiseau, France*; Y. Liu,* Dalian University of Technology*; I. Korolov, A. Derzsi,* Hungarian Academy of Sciences*; E. Schuengel, M. Koepke,* West Virginia University*; T. Mussenbrock,* Ruhr-University Bochum, Germany*; E.V. Johnson, T. Lafleur, J.-P. Booth,* Ecole Polytechnique, Palaiseau, France*; D. O'Connell, T. Gans,* University of York, UK*; YN. Wang,* Dalian University of Technology*; Z. Donko,* Hungarian Academy of Sciences **INVITED**

The spatio-temporal dynamics of charged particles and the formation of ion energy distribution functions (IEDF) are investigated in electronegative capacitive RF plasmas operated in CF_4 based on a combination of experiments, PIC simulations, and models. In the experiment, Phase Resolved Optical Emission Spectroscopy is used to access the space and time resolved electron dynamics. The DC self bias and IEDFs are measured at the electrodes. For a single frequency discharge operated at 13.56 MHz

[*] **Coburn & Winters Student Award Finalist**

and 80 Pa we demonstrate that the presence of an electronegative gas can change the electron power absorption dynamics completely compared to electropositive gases by inducing a heating mode transition. Reducing the driving frequency results in the formation of stable striations of the optical emission and electron impact excitation rate due to the collective response of positive and negative ions to the driving frequency. Based on this fundamental understanding, we show that tailoring the driving voltage waveform using a superposition of multiple consecutive harmonics of a fundamental frequency with individually adjustable harmonics' amplitudes and phases allows for control of the DC self bias, the shape and mean energy of the IEDF, the electron power absorption dynamics, and the spatial division of the discharge into two halves of strongly different electronegativity.

11:40am **PS-TuM12 Correlation of III/V Semiconductor Etch Results with Physical Parameters of High Density Reactive Plasmas Excited by Electron Cyclotron Resonance**, ***Gerhard Franz,*** Munich University of Applied Sciences, Germany*; R. Meyer, M.-C. Amann,* Technische Universität München, Germany

Reactive ion etching is the interaction of reactive plasmas with surfaces. For a

detailed understanding, significant properties of reactive composite low pressure

plasmas driven by electron cyclotron resonance were investigated and compared with

the radial uniformity of the etch rate. The determination of electronic properties

of chlorine and hydrogen containing plasmas enabled the understanding of the

pressure dependent resonance behavior and gave a better insight into the

electronic parameters of reactive etch gases. With electrical evaluation of

I(V) characteristics obtained with a Langmuir probe, differently composed

plasmas were investigated and the most important methods of analyzing the I(V)

characteristics were compared. A mathematical model to reduce noise sensitivity

was used and compared to the standard method of Druyvesteyn to derive the electron

energy distribution functions. Special attention was payed to the power of the

energy dependence in the exponent. Especially for plasmas which are generated by

electron cyclotron resonance with EM modes, the existence of Maxwellian

distribution functions are not to be taken as a self-evident fact, but it was

proven for Ar- and Kr-stabilized plasmas. Aside from the electron temperature,

which could be derived within a certainty of ten percent using the discussed

methods, the global uniform discharge model of Lieberman has been shown to be

useful to calculate the neutral gas temperature. To what extent the invasive

method of using a Langmuir probe could be replaced with the non-invasive

optical method of emission spectroscopy, especially actinometry, was

investigated and the resulting data showed the same relative behavior as

Langmuir data.

12:00pm **PS-TuM13 Mapping Plasma Potential of Rotating Ionization Zone in DC Magnetron Sputtering**, ***Matjaz Panjan,*** Lawrence Berkeley National Laboratory, Slovenia*; A. Anders,* Lawrence Berkeley National Laboratory

In the magnetron discharges formation of dense plasma structures, called ionization zones or spokes, have been extensively studied over the last few years. Ionization zones were first observed in high power impulse magnetron sputtering (HiPIMS) [1] and later in DC magnetron sputtering (DCMS) [2]. In DCMS discharges operated at low-currents and low-pressure a single ionization zone forms with the shape of an elongated arrowhead and rotates in the direction opposite to the electron drift (i.e., in the -**E**×**B** direction). In this work we used emissive and floating probes to measure plasma and floating potentials of rotating ionization zone for a magnetron with a 3" niobium target operated at 2 mTorr (0.27 Pa), -270 V and 100 mA. Both probes showed strong temporal and spatial variations of the signals. From the measurements in the radial and axial directions we reconstructed full three-dimensional distributions of the plasma potential. The potential distribution was compared with the images recorded by an intensified CCD camera. Strongest light intensities in the zone corresponded to maximum plasma potential (i.e., ~0 V for probe positioned over the racetrack and for axial distances above 5 mm), whereas weaker light intensities corresponded to negative potentials (e.g., -70 V for the probe positioned over the racetrack and 5 mm away from the cathode). The plasma potential distribution matches with a previously suggested potential hump model [3]. Sharp drops in the light intensity are associated with large potential gradients, which result in strong in-plane electric fields. The largest in-plane fields are found in the azimuthal direction at the edge of the ionization zone (up to 10 kV/m). Weaker electric fields also form in the radial direction. The presence of the in-plane electric fields changes the paradigm of predominantly axially-directed electric fields. From the plasma potential we calculated the space charge distribution. A double layer is present around the edge of the ionization zone with higher ion density inside the zone and higher electron density just behind the zone's edge. From the difference between the plasma and floating potentials we also reconstructed the three-dimensional distribution of electron temperature. Electrons have largest energies in the area of highest light intensity (i.e., inside the zone and close to the edge) whereas their energy decreases along the drift direction in correlation with the fading light intensity.

[1] A. Anders *et al.*, *J. Appl. Phys.*, **111** (2012) 053304

[2] M. Panjan *et al.*, *Plasma Sources Sci. Technol.*, **24** (2015)065010

[3] A. Anders *et al.*, *Appl. Phys. Lett.*, **103** (2013) 144103

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