Plasma Science and Technology Division
Room 104A - Session PS-ThA

Plasma Diagnostics, Sensors and Controls

Moderator: Steven Shannon, North Carolina State University

2:20pm **PS-ThA1 In-situ Measurement of Electron Emission and Electron Reflection Yields***, **Mark Sobolewski,*** National Institute of Standards and Technology (NIST)

Bombardment of plasma-exposed surfaces by energetic particles causes electrons to be emitted, which in turn influence the plasma. Accurate plasma simulations require knowledge of the flux or yield of emitted electrons. Yields can be measured directly in beam studies, but it is impractical to produce a beam of each possible energetic particle produced by typical plasmas. In contrast, in-situ measurements, performed during plasma exposure, provide useful values for effective or total electron emission yields, summed over all the energetic particles present for given plasma conditions. Here, measurements were performed at 5-10 mTorr in a radio-frequency (rf) biased, inductively coupled plasma (icp) system. The rf voltage and current across the sheath adjacent to the rf-biased electrode are measured, along with Langmuir probe measurements of ion current density and electron temperature. The measurements are analyzed by a numerical sheath model, which allows the current of electrons emitted from the surface to be distinguished from other mechanisms of current flow. An insulating cap placed on the rf-biased electrode exposes a small, off-center portion of its area. The cap, combined with the azimuthal electric field generated by the icp source, allows outgoing, emitted electrons to be distinguished from electrons reflected at the counterelectrode surface. Thus we obtain values for the total yield or flux of electrons emitted at the rf-biased surface and the reflection coefficient at the counterelectrode. The technique is validated by comparing measurements made in argon discharges with literature results and then is applied to characterize yields at practical surfaces in inert gas plasmas and fluorocarbon etching plasmas.

2:40pm **PS-ThA2 Electron Energy Distribution Measurements in Dusty Non-thermal Plasmas***, **Austin Woodard**, L. Mangolini,* University of California, Riverside

Dusty plasmas are a peculiar class of plasmas characterized by the presence of charged solid particles. Understanding the properties of these environments, ever-present in laboratory discharges, represent a crucial requirement for the engineering and optimization of several plasma-based processes employed in industrial manufacturing, such as thin film fabrication and etching. Langmuir probe measurements represent a well-established method used for the investigation of the properties of plasma discharges, such as the electron density, the ion density, the electron temperature and the electron energy distribution function (EEDF). In dust-rich plasmas, however, the application of the Langmuir probe method is quite challenging as the dust particles quickly form an insulating film on the probe surface which may hinder a reliable measurement. In this contribution, Langmuir probe measurements are performed in an inductively coupled RF Ar-H_2 primary plasma which is dosed with conductive nanoparticles produced in a secondary RF plasma reactor. To avoid the formation of an insulating coating, graphitic carbon nanoparticles, obtained in the secondary reactor from the dissociation of C_2H_2 in an Ar-H_2 plasma, are used for this study. The conductive graphitic nanoparticle coating formed on the probe tip does not negatively impact EEDF measurements in a pristine Ar-H_2 plasma, allowing a more forgiving environment in which to study the effect of dust on plasma properties. The EEDF is obtained through the Druyvesteyn method, via the second-derivative of I-V probe characteristics. Electron densities and temperatures are obtained from the EEDF measurements, while ion densities are calculated from the I-V characteristics. The role of process parameters such the nanoparticle density and the primary plasma input power is carefully mapped. The nanoparticle density is measured through the mass injection rate into the primary reactor, allowing for the particle charge to be measured across the parameters. In the dust-free pristine Ar-H_2 plasma, a transition in the primary ion is observed as a function of the applied RF power: H_3^+ appears to dominate at low powers, transitioning to Ar^+ at higher values. In dusty environments, the measured plasma power is much lower than in pristine, prompting H_3^+ as a likely choice for the primary ion in ion density calculations. As expected from theory and previous literature, nanoparticles act as electron sinks, reducing the electron density inside the plasma volume, resulting in an increased electron temperature to maintain ionization events; contrary to theory, however, the electron temperature increases with increasing input plasma power.

3:00pm **PS-ThA3 The Surface Plasmon Energy and the Secondary Electron Emission on an Oxidized Aluminum Surface***, J.-T. Li, J. Qiu, **Yi-Kang Pu**,* Tsinghua University, China **INVITED**

The energy evolution of surface plasmons and the apparent secondary electron yield on an aluminum surface during the oxidation process are investigated in an experiment under a controlled environment. The surface plasmon energy is determined from the location of the surface plasmon loss peak in the EELS spectra; at the same time, the total oxygen coverage (in the submonolayer regime) and the oxide layer thickness (in the multilayer regime) are obtained from the peak profiles of O 1s and Al 2p photoemission lines in the XPS spectra. The apparent secondary electron yield is deduced from the breakdown voltage between two parallel plate electrodes in a 360 mTorr argon environment using a Townsend breakdown model. In the submonolayer regime, both the surface plasmon energy and secondary electron yield decrease with the total oxygen coverage. In the multilayer regime, the surface plasmon energy continues to decrease with the oxide layer thickness although the rate of decrease is lower. However, the secondary electron yield sharply increases with the oxide layer thickness. In this presentation, we will discuss possible mechanisms for the variation of these quantities and compare the measured results with that from the models.

4:00pm **PS-ThA6 Transient Phenomena in Power Modulated Chlorine Plasma***, **Priyanka Arora**, T. List, T. Ma,* University of Houston*; S. Shannon,* North Carolina State University*; S. Nam,* Samsung Electronics Co., Ltd., Republic of Korea*; V.M. Donnelly,* University of Houston

Power-modulated plasmas (i.e. rapid switching from high to low power) could have some potential advantages over conventional pulsed plasmas (where power is periodically turned completely off) for plasma processing in that a larger parameter space is available between fully pulsed and continuous power. In the present study, power at 13.56 MHz applied to a mostly chlorine inductively-coupled plasma was modulated between a high power and low power state. Time-resolved optical emission, Langmuir probe, and forward and reflected power measurements were performed. Two distinct types of transient phenomena were found upon switching from the high power to low power state. In a “normal” mode, electron temperature (T_e) remains constant, while electron and ion number densities (n_e and n_i^+) and optical emission intensities smoothly drop to a level roughly equal to the fractional drop in power. In a second “anomalous” mode, n_e, T_e and optical emission intensities rapidly drop and stay low for an extended period before rising to values commensurate with the drop in power. Under many circumstances, a single delay time is found that depends on pressure and power duty cycle. In some cases, two delay times can be found, with subtle changes in matching network settings causing one delay time or the other. The anomalous mode can exhibit complex behavior such as two or three phases in the low power period, and periodicity at half the pulsing frequency. The anomalous mode will be discussed in terms of negative ion-driven instabilities.

4:20pm **PS-ThA7 Measurements of RF Magnetic Fields and Plasma Current in Coupled Low and Very High Dual-Frequency Plasma Sources***, J.P. Zhao, P.L.G. Ventzek, B. Lane,* Tokyo Electron America, Inc.*; **Toshihiko Iwao**, K. Ishibashi,* Tokyo Electron Technology Solutions Ltd., Japan

Plasma processing systems capacitively driven at very high frequencies (VHF, e.g. 100MHz) have attracted much interest for semiconductor and flat panel display processing. VHF has the advantage of generating plasma with more efficiency as power is coupled more into electrons and less into ions in the sheath. Benefits are seen for processes requiring reduced ion energy, ostensibly to minimize damage, high ion and radical flux to the substrate. The benefits of VHF are accompanied by challenges. The short wavelength associated with VHF power is reduced even further in the presence of high density plasma. The wavelengths are comparable to the RF electrode dimension. As a result, spatial variations in plasma density and sheath voltage can arise and lead to undesired non-uniformities in process parameters. Skin effects associated with high plasma density and plasma-sheath local resonances are other destroyers of plasma uniformity. Previously, we have reported[1] a detailed investigation on the spatial and temporal evolution of RF magnetic field and plasma current in a 100MHz plasma source performed with a magnetic field probe (B-dot loop). The probe translated across the diameter of the VHF plasma measured the magnitude and phase of the fundamental and harmonics of the plasma excitation frequency as a function of radial position. The measured magnetic fields displayed a transition from simple to complex behaviors depending on plasma conditions. The spatiotemporal resolved magnetic field exhibits a series of fast current reversals and subsequent circulation driven by inward wave propagation that are electromagnetic in nature. We showed how the onset, frequency and amplitude of the current reversal and subsequent circulation were strongly related to applied plasma conditions. We also showed that plasma current derived from the magnetic field distribution was closely correlated to the plasma density profile measured by a plasma absorption probe. In order to further understand these fundamental electromagnetic structures in VHF plasma, in the current study, we apply LF on top of the VHF aimed to modify the electromagnetic structures. Performed with B-dot probe, we report the spatial and temporal evolution of VHF magnetic field and plasma current as a function of different LF phases as well as the detailed correlation of VHF electromagnetic structure and the LF modulated plasma sheath variation. We show that the coupling of the VHF electromagnetic field to the plasma strongly depends on the phase of the LF driven source. Measurements are compared against different theories for how the VHF power couples to the plasma.

[1] PS+VT-ThA12, 64th AVS Symposium, Tampa FL

4:40pm **PS-ThA8 Self-neutralized Nearly Monoenergetic Positive Ion Beam Extracted From a Pulsed Plasma***, **Ya-Ming Chen**, R. Sawadichai,* University of Houston*; S. Tian,* Lam Research Corporation*; V.M. Donnelly, D.J. Economou, P. Ruchhoeft,* University of Houston

Space charge neutralization of an ion beam extracted from a plasma is crucial for advanced plasma processes which require precise control of the ion flux and the width of the ion energy distribution (IED). In previous studies, filaments thermionically emitting electrons were used for neutralizing the space charge, which would otherwise cause the ion beam to diverge owing to Coulomb explosion.[1, 2] However, the performance of the neutralizing filaments is restricted by their limited lifetime and required extra power supplies. This work reports that a self-neutralized positive ion beam can be extracted from a pulsed plasma. In particular, a nearly monoenergetic ion beam was realized by applying a synchronous DC bias in the afterglow (plasma-off) of the plasma. A mechanism of the self-neutralization process is proposed based on space-time resolved ion and electron current (I_i and I_e) measurements done by a movable Faraday cup. The measurements revealed that electrons from a low-density plasma immediately downstream of the ion extraction grid neutralize the space charge in the beam transport region. Time-resolved plasma potential measurements suggest that there could be two periods for low-energy ions and electrons to leave the source and form the low-density plasma in the downstream of the ion extraction grid. Among the observations are 1) with increasing distance, d, from the grid $I_e > I_i$ at d = 1-5 cm, $I_e = I_i$ at d ≈ 20 cm, and $I_e << I_i$ at d > 30 cm; 2) I_i decays by less than $1/r^2$; 3) electron energy peaks at ~30 eV, ascribed to acceleration by the 100 eV ion beam transiting through the downstream plasma. Ion flux and IEDs were also studied using a retarding field energy analyzer (RFEA). Detailed explanations for the self-neutralization process will be described.

Work supported by NSF.

References

[1] R. G. Jahn, *Physics of Electric Propulsion*. (Courier Corporation, 2006).

[2] J. P. Chang, J. C. Arnold, G. C. H. Zau, H.-S. Shin and H. H. Sawin, *J. Vac. Sci. Technol A*:

15 (4), 1853-1863 (1997).

5:00pm **PS-ThA9 Diagnostics of Plasma Neutral Species in a Very High Frequency Oxygen Plasma with High Sensitivity Broadband Absorption Spectroscopy***, **Jianping Zhao**, P.L.G. Ventzek, B. Lane,* Tokyo Electron America, Inc.*; T. Iwao, K. Ishibashi,* Tokyo Electron Technology Solutions Ltd., Japan*; J.-P. Booth,* CNRS, Ecole Polytechnique, France

As advanced memory and logic critical dimensions shrink and stack complexity, film quality and yield requirements increase, precision plasma processes including plasma enhanced atomic layer deposition (PEALD) and atomic layer etch (ALE) experience more demand. Ideally infinite selectivity and damage-free process results with sub-angstrom control are sought. Plasma enhanced processes, particularly PEALD rely on plasma generated radicals for much of their perceived benefit. Furthermore, in both atomic layer etch and deposition processes, low or nearly zero energy ions are required. Large-area plasma processing systems capacitively driven at very high frequencies (VHF, e.g. 100MHz) have attracted much interest for semiconductor device and flat panel display processing. VHF has the additional advantage of generating plasma with more efficiency as power is coupled more into electrons and less into ions in the sheath. Benefits are seen for processes requiring reduced ion bombardment energy, ostensibly to minimize damage and high radical flux to the substrate. Unfortunately, it has been a challenge to measure the neutral plasma species of interest. It would be desirable to use plasma absorption spectroscopy to study plasma neutral species because it can provide direct measurement of the absolute densities of species in their ground state as well as vibrational and rotational properties of neutrals. Lack of intense and stable light sources with wide wavelength coverage and the lack of optical aberration-free spectrographs and detectors with true high resolution has rendered plasma absorption spectroscopy impractical as a solution for industry. Emission based diagnostics such as actinometrical methods are far too imprecise. A recent advance, broadband plasma absorption spectroscopy[1] (BPAS) has been proven to be a very practical improvement of plasma absorption spectroscopy with capability to detect absorbance as low as 1×10^{-4}. In order to understand the fundamental plasma chemistry property of VHF plasma, we present here the measurement of the plasma neutral properties with a high sensitivity BPAS technology. Illustrative measurements were performed in a 100MHz plasma source with pure oxygen plasma spanning a wide RF power and pressure range. Vibrational and rotational properties of O_2 molecules are derived from a theoretical fitting to the experimental spectra. Density of O_2 molecule at different vibrationally excited levels are also derived. Effects of VHF power and pressure on these plasma neutral properties are reported.

[1]Mickaël Foucher, Daniil Marinov, Emile Carbone, Pascal Chabert, and Jean-Paul Booth, Plasma Sources Sci. Technol. 24 (2015) 042001

5:20pm **PS-ThA10 Development of the Virtual Metrology Using a Plasma Information Variable (PI-VM) for Monitoring SiO_2 Etch Depth***, **Yunchang Jang**, H.-J. Roh, S. Ryu, J.-W. Kwon, G.-H. Kim,* Seoul National University, Republic of Korea

Advanced process control (APC) has been attracting attention as a technology to enhance process yield and it requires accurate and reliable virtual metrology (VM). Accuracy of VM is determined by how sensitively the input variables reflect the drift and changes of the process environment. Many previous approaches to improve the performance of VM have been focused on development of the statistical methods to select the valuable input variables from the equipment data and additional sensor data such as optical emission spectroscopy (OES) and plasma impedance monitors (PIM). In this study, the noble variables, named plasma information (PI) variables are introduced, which are obtained by phenomenological analysis and they are added into the VM development. Then we evaluated its contribution to improve the accuracy of VM. It notes that PI variables represents the state of etch plasma so it can be used to monitor the variation of process results in plasma-assisted semiconductor fabrication process. Effect of PI variables on improving VM accuracy has been investigated through following conventional (or standard) VM development procedures as follows; 1. preprocess of input dataset, 2. data exploration, 3. variable selection, 4. training of a model, and 5. Validation of the model. We added PI variables in the steps (i) in-between 2 and 3 steps (called $PI\text{-}VM_{STA}$) and (ii) in-between 3 and 4 steps (called VM_{STA}+PI). Each VM model are developed and evaluated by using 50 sets of SiO_2 etching depth data, having 20:1 aspect ratio and less than 5 % of variation. PI_{EEDF}, representing variation of electron energy distribution function (EEDF) is obtained from analysis of OES, which is based on the argon excitation kinetics. Pearson's correlation filter, principal component analysis (PCA), and stepwise variable selection are used for the variable selection methods. Results show that VM models using PI_{EEDF} have better performance than any other conventional VM models because PI_{EEDF} has much higher correlation with output variable than the other equipment and sensor variables. Especially, $PI\text{-}VM_{STA}$ using stepwise variable selection method shows the highest accuracy where PI_{EEDF} provides a basis to select other OES variables. This study shows that a phenomenological-based, statistically tuned VM can be developed by using PI variables as input. It has advantages for management of dataset and selection of control variables in APC application.

5:40pm **PS-ThA11 Model Predictive Control of Plasma Density in Ar/SF_6 Capacitively Coupled Plasma Source***, **Sangwon Ryu**, H.-J. Roh, Y. Jang, D. Park, J. Koo, J.M. Lee, G.-H. Kim,* Seoul National University, Republic of Korea

Advanced Process Control (APC) of plasma assisted processes has drawn interests because the reproducibility of process results is degraded by continuous deterioration of the equipment. To control the process drift, the process plasma should be maintained by in-situ controller. Some earlier researches handled real-time feedback proportional integral derivative

(PID) controllers for plasma density which is coupled to generation of the reactive species in plasma assisted processes. However, since PID had no knowledge of the controlled system, PID couldn't guarantee optimal control especially for systems with long dead time. Thus, we proposed model predictive controllers (MPC) for plasma density in Ar/SF_6 etching plasma as the control model of the MPC contains information of the system. To provide plasma density to the controller in real-time, we developed plasma density monitoring module which used light emissions from Ar measured by a spectrometer. The method showed $R^2 = 0.99$ with plasma density measured by Langmuir probe. The control model of the MPC was set as First Order Plus Dead Time (FOPDT) model which consisted of the linear gain and the time constants. We trained the control model with sensitivity tests; observing variation of plasma density as changing RF power. Compared to PID, MPC showed 6 times shorter settling time in set point tracking tests. Also, the integral of the absolute error for the MPC was 4 times lower than that of PID in same tests. The experimental results showed that MPC could control plasma more effectively than PID could by predicting the dead time of the system included in the control model. From the analysis on the parameters of the control model, we explained the control model as function of system parameters; the linear gain represented the balance between the power absorbed by electron and the power lost by electron impact collisions and the time constants were composed of the data transfer time between devices and the actuation time of the devices. This study showed that MPC could be used as the etching process plasma controller which would be a part of APC.

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