Plasma Science and Technology
Room 124 - Session PS-ThA
Plasma Sources. Diagnostics and Control II

Moderators: David Boris, U.S. Naval Research Laboratory, **Necip Uner**, Middle East Technical University

2:15pm **PS-ThA-1 Si Etch Characteristics in an Ultra-Low Electron Temperature CF_4 Plasma**, *C. Chung, **Junyoung Park**, N. Kim, J. Choi, U. Jung, J. Jung, M. Kim,* Hanyang University, Korea

The etching characteristics of Si in an ultra-low electron temperature (ULET, T_e~0.7 eV) CF_4 plasma using a grid are investigated. Si etching is performed in the ULET CF_4 plasma, and the etch profile of Si is obtained by a Field Emission Scanning Electron Microscope (FE-SEM). When the substrate bias power is not applied, the etch profile of Si in an inductively coupled plasma (ICP, T_e~2 V) shows a rounded shape of the trench, while the etch profile of Si in the ULET plasma shows a flat shape. When a DC pulse bias voltage is applied to the ULET plasma, the etch profile shows a flat shape trench. However, when a substrate bias voltage frequency is 12.56 MHz, the electron temperature is increased and then the etch profile at the bottom of the trench shows a rounded shape as the bias voltage increases. These results show that the ULET plasma has a significant impact on the etch profile, which seems to be the reduction in charge accumulation in the trench due to the low electron temperature.

2:30pm **PS-ThA-2 Temporal Evolution of Plasma Parameters and Electron Energy Distribution in a Pulsed-Modulated Capacitively Coupled Plasma**, ***Satadal Das,*** University of Illinois at Urbana-Champaign; *D. Ruzic,* University of Illinois at Urbana Champaign

Electron energy distribution function (EEDF) controls the production of any radical/species in plasma and the ion energy distribution on the substrate. In recent years, the pulsed-modulated capacitively coupled rf (PM-CCRF) plasma has gained much attention in the semiconductor industry due to the variations of electron temperature and plasma density over a wide range with the operating controls, i.e., the pulse repetition frequency, duty cycle and pulse shape. Recently, our group in CPMI, UIUC proposed a novel concept for controlling the time resolved EEDF at the substrate in a high-power impulse magnetron sputtering (HiPIMS) discharge. In our present work, we study the time resolved plasma parameters and EEDF for various rf powers and working gas pressures in the steady-state plasma and the effect of PM-CCRF on time resolved EEDF.

In our experiment, argon plasma is produced between two parallel-plates with 13.56 MHz rf supply. An external function generator is used for pulsing the rf power supply. An in-house developed single cylindrical Langmuir probe and two different measuring circuits are used to collect the I-V characteristics of plasma. We observe that in the steady-state condition both the plasma potential and density increase four times over the rf cycle. For the argon pressure of 5.7 mTorr (~ 0.76 Pa), the plasma potential and density reach at 33±0.65 Volts and $(4.2\pm0.5)\times10^{15}$ / m^3 respectively. We also measure the time resolved EEDF over the complete rf cycle and it does not change with rf times. However, the shapes are broadly like Maxwellian curve. From the EEDF we calculate the effective electron temperatures (T_{eff}) and it remains constant at 12±0.24 eV over the rf cycle. We also observe that both the plasma density and potential increase with increasing the rf power over the complete rf cycle; however, T_{eff}reduces. During the PM-CCRF, we measure the higher T_{eff} than the steady-state, i.e., 14.67±0.36 eV and it also does not change over the rf cycle. It is important that our measured EEDF gives the density of high energetic tail electrons (up to 50 eV) which are present in plasma. The experimental observations will be discussed in detail during the presentation.

2:45pm **PS-ThA-3 Probing Microwave-Driven Plasmas: Investigating Ar Metastable Densities in Ar/N_2 Mixtures via LIF Technique**, ***Nafisa Tabassum**, C. Dechant,* North Carolina State University; *A. Zafar,* Appled Materials; *D. Peterson, T. Chen,* Applied Materials; *S. Shannon,* North Carolina State University

The spatial and time-resolved density of metastable Ar species in microwave-driven plasmas operating at 2.45 GHz is systematically investigated by Laser-Induced Fluorescence (LIF). Effects of gas pressure and microwave power are investigated in the range of 70-200 mTorr and 25-150 W. LIF measurements involve the targeted excitation of metastable atoms using a tunable Nd:YAG laser producing nanosecond duration laser pulses at 100 Hz. The laser is tuned at 696.73 nm to pump the metastable $(^2P^0_{3/2})4s\ ^2[3/2]^0$, J=2 level to the $(^2P^0_{1/2})4p\ ^2[1/2]$, J=1 level. The fluorescence is observed from decay to the $(^2P^0_{3/2})4s\ ^2[3/2]^0$, J=1 level at 727.49 nm. The fluorescence is captured using an ICCD camera along with a bandpass filter centered at a wavelength of 730 nm with 10 nm FWHM bandwidth. The LIF intensity correlates with the expected variation in metastable density. A large density gradient is observed that correlates with power and pressure. Furthermore, the study extends to mapping the population density of metastable atoms by introducing nitrogen admixture (ranging from 0 to 20 %) into the argon plasma environment. The natural lifetime of fluorescence for pure argon and the impact of introducing nitrogen is examined. The effects of varying pressure, power levels and the quenching rate, are examined through fluorescence decay. Additionally, the experimental findings are compared with simulations conducted using the Multiphysics Object Oriented Simulation Environment (MOOSE) platform.

3:00pm **PS-ThA-4 Diagnostics of Plasma Parameters and Surface Impedance by Measuring AC Probe Current at Harmonic Frequencies**, ***Junki Morozumi**, K. Eriguchi, K. Urabe,* Kyoto University, Japan

To understand the physical and chemical interaction between plasma and material, a methodology to diagnose both plasma and surface properties is necessary. From a physical point of view, the system consisting of bulk plasma, ion sheath, surface (modified) layer, and bulk material can be electrically modeled by a series of nonlinear resistance of the ion sheath and RC parallel circuit of the surface [1]. We have demonstrated that the impedance of the surface layer can be characterized during plasma exposure by measuring the amplitude and phase of the current flowing in the material with applying an AC voltage at various frequencies [2]. To obtain the plasma parameters, a method to analyze the nonlinear resistance of the ion sheath by measuring the current at harmonic frequencies of the applied AC voltage has been developed [3]. In recent years, we have studied the influence of the impedance of surface-modified layers on the generation of harmonic currents to develop a method to monitor plasma parameters and surface impedance simultaneously. In this study, we performed simultaneous monitoring of the plasma parameters and the surface resistance using a single metal probe in a reactive plasma generated in low-pressure Ar/O_2 gas. First, we analyze the nonlinear resistance of the ion sheath by applying AC voltage to the probe at a frequency where the surface impedance can be negligible. (>10 kHz in our system) Then, we calculate a relationship between the surface resistance and the amplitudes of harmonic currents at a frequency where the RC parallel circuit of the surface layer can be considered as a resistance. (<100 Hz) From these analyses and measurement data of the harmonic currents at the low frequency, we decide the surface resistance. By applying the AC voltage at the high and low frequencies alternately, we continuously measured the plasma parameters (electron temperature and ion density) and the surface resistance with a temporal resolution of approximately 10 s. The experimental results obtained in various discharge conditions indicate that the developed method can contribute to advanced control of plasma processing by providing data on plasma and surface properties.

[1] R. A. Olson, J. Appl. Phys. **43**, 2785 (1972).

[2] J. Morozumi *et al*., Jpn. J. Appl. Phys. **62**,SI1010 (2023).

[3] M.-H. Lee *et al*., J. Appl. Phys. **101**, 033305 (2007).

3:15pm **PS-ThA-5 Plasma Diagnostics with a Transparent(ITO) Probe Based on the Floating Harmonic Method**, *C. Chung, **Beom-Jun Seo**, H. Nahm, D. Kim,* Hanyang University, Korea

The floating harmonic method is commonly employed for plasma diagnostics in semiconductor processing. From the ratio of harmonic currents flowing through a floating probe in the plasma, parameters such as electron temperature and ion density can be measured. This technique is effective even when the probe is contaminated or coated with a thin dielectric film. In this study, we propose a diagnostic method that uses a floating probe with a tip made of ITO glass. By applying nonlinear circuit analysis and high-frequency voltage, we could have developed this novel approach. The primary advantage of our method is the ability to acquire both electrical and optical measurements simultaneously at the same location on the chamber wall. This dual measurement capability compensates for the inherent limitations of each individual measurement type, thereby significantly improving the accuracy and comprehensiveness of plasma diagnostics. We measured plasma parameters using the floating probe and performed optical emission spectroscopy measurements through the ITO glass.

3:30pm **PS-ThA-6 Time-Resolved Ion and Neutral Energy Distribution Function Study of High-Power Impulse Magnetron Sputtering with Positive Cathode Reversal using a Linear Magnetron** *, **Tag Choi**, Z. Jeckell, S. Pickholtz, J. Miles, D. Qerimi, D. Ruzic,* University of Illinois at Urbana-Champaign

High-Power Impulse Magnetron Sputtering (HiPIMS) plasma is one of the physical vapor deposition (PVD) techniques that utilizes very short voltage pulses and a high peak currents. It can produce higher ionization fraction and denser plasma compared to conventional DC or pulsed DC magnetron sputtering, resulting in higher quality thin films such as denser films, smoother film surfaces, and better adhesion. Several years ago, positive cathode reversal technique was introduced to the HiPIMS sources, which reverses the polarity of the cathode to increase the energy of ions. This work aims to investigate the time-resolved ion and neutral energy distribution functions (IEDF/NEDF) of HiPIMS with positive cathode reversal discharge on a large area linear magnetron using Plasma Sampling Mass spectrometer (PSM) from Hiden Analytical Inc. This work includes IV traces of each pulse, which is used to confirm that the plasma produced is in HiPIMS plasma regime. Ultimately, a better understanding of HiPIMS plasma can contribute to improving film quality such as increasing uniformity, reducing stress, enhancing conductivity, and improving crystallinity. In this study, titanium (Ti) and tungsten (W) targets are utilized while parameters such as main pulse length between 10 – 100 us, peak current between 40 – 400 A, positive pulse length between 20 – 200 us, with/without positive voltage of the cathode, etc. are varied to understand how HiPIMS plasma properties vary.

3:45pm **PS-ThA-7 A Plasma Diagnostic Based Approach to Enabling Low Run-In for Sputter Deposited MoS_2 Solid Lubricants***, **Steven Larson**, A. Ming, T. Babuska, M. Dugger, F. DelRio, M. Rodriguez, R. Kolasinski, J. Curry,* Sandia National Laboratories

Sputter deposited molybdenum disulfide (MoS_2) coatings have long been utilized as dry lubricants for aerospace applications because of their ultra-low friction and high performance in vacuum. Historically, sputter deposited MoS_2 films have faced challenges such as low density, poor aging resistance, and inconsistent performance across batches due to variability in material properties. To overcome these issues, the industry resorted to doping MoS_2 coatings with various metals (Ni, Ti, Al, Pb, Au, WSe) and nonmetals (Sb_2O_3, PbO, C), which, while improving density and consistency, undesirably increased initial friction, particularly after aging. In this study we present using a modern, plasma diagnostic based approach to develop high performance undoped MoS_2 coatings. Using these methods, we tie deposition parameters directly to ion flux and energy, and eventually to the resulting material properties (crystallinity, hardness, modulus, and stoichiometry) and tribological performance (friction, run-in, and wear rate) of the of the deposited films. The resulting undoped MoS_2 coatings demonstrate a near bulk density, and maintain an ultra-low initial friction, both before and after aging. Sandia National Laboratories is managed and operated by NTESS under DOE NNSA contract DE-NA0003525. SAND2024-06329A

4:00pm **PS-ThA-8 Investigations of Focus Ring Electrodes in Inductively Coupled Plasma***, **Tugba Piskin**,* LAM Research*; S. Nam, H. Lee,* Samsung Electronics Co., Inc., Korea (Democratic People's Republic of)*; M. Kushner,* University of Michigan, Ann Arbor

The microelectronics fabrication tools have progressed significantly to cover the demand and decrease the cost of ownership. The substrate biases are often used in inductively coupled plasma tools to control ion energy and angle distributions. However, applying bias to the electrode under the wafer can further cause sheath bending, resulting in poor ion angle distribution at the wafer edge. The plasma configuration at the wafer edge, due to sharp electrical, chemical, and thermal gradients, causes non-uniform deposition and etch profiles in microelectronics processing.

The investigations were carried out for the secondary (ring) electrode located in the focus ring, in addition to the electrode under the wafer. The Ar/O_2:80/20 ICP operating at 10 mTorr with 450 W of continuous power was modeled with Hybrid Plasma Equipment Model (HPEM). The ion energy and angles at the edge of the wafer were tracked closely to observe changes. The improvement in the ion angles at the wafer edges was observed under various operating conditions. Parametric studies were completed by altering the operating conditions of the ring electrode and materials of the focus ring and chuck. It was found that the voltage of the ring electrode was the main control knob to achieve anisotropic profiles on the wafer edge. The ion energy and angle distributions will be presented with standard and proposed configurations in the parametric studies for bias voltages and materials.

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Author Index

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