Plasma Science and Technology
Room: Galisteo - Session PS2-TuM

Plasma Diagnostics, Sensors and Control
Moderator: U. Czarnetzki, Ruhr-University Bochum, Germany

8:00am **PS2-TuM1 Wafer-level Plasma Parameters Measurements in a Multi-Frequency Capacitively Coupled Plasma Discharge**, ***L. Dorf***, *S. Rauf, J.A. Kenney, K. Bera, N. Misra, K. Collins*, Applied Materials Inc.

Two complications with wafer-level measurements in a capacitively coupled plasma (CCP) discharge are very high DC (~ -1kV) and radio-frequency (RF) (~2kV peak-to-peak) voltages of the substrate, and the lack of theoretical basis for interpretation of volt-ampere characteristics (VACs) of the probes inside the RF sheath. In this work, we present the diagnostic apparatus that measures ion current to the wafer, along with near-sheath plasma density (n_e) and electron temperature (T_e). Particle-in-cell (PIC) and fluid plasma simulations are used to help interpret collected VACs. Measurements are performed using a set of radially distributed planar double probes (DP). The electronic circuit located outside of the discharge chamber provides: (1) DC isolation and RF filtering of the high voltage, (2) biasing voltage to the probes, (3) switching between the probes, and (4) probe current measurements. Electrical signals are brought in and out of the chamber using a specially designed feed-through and a low-profile connection to the substrate. Results of wafer-based measurements performed in an Applied Materials CCP chamber at a variety of rf-frequencies (2, 13, 162 MHz), rf power levels (300 – 1000 W), neutral fill pressures (30 – 100 mT), chemistries (Ar, O2, Ar/CF_4), and magnetic field configurations are presented. At low frequency, pressure was found to have stronger effect on ion current and plasma density than that at intermediate and high frequencies; in all chemistries. The effect of mixing low and medium frequencies with the high frequency was found to be most pronounced at the periphery of the discharge. Magnetic field was confirmed to be a powerful knob for controlling radial uniformity of the discharge at all frequencies; namely, edge current and density tend to increase with application of the magnetic field. To interpret VACs, a 2-dimensional fluid plasma model was developed for the CCP chamber with a DC-biased pad on the substrate. This model was used to calculate current at the DC-biased pad versus applied DC voltage, i.e. single probe (SP) VAC. The SP VACs for a variety of discharge rf-voltages and neutral pressures were then used to derive the DP VACs, which were in turned analyzed using standard experimental techniques to obtain plasma parameters. Those were found to be in a good agreement with near-sheath plasma parameters calculated self-consistently by the fluid model. PIC simulations confirm the results of fluid simulations, but also highlight the highly non-equilibrium nature of electron energy distribution at the electrode.

8:20am **PS2-TuM2 In-situ Measurement of High-Frequency Current and Voltage in Etching Chambers**, ***S. Kobayashi***, *H. Hanawa, K. Ramaswamy, S. Rauf*, Applied Materials Inc.

A set of electrical probes have been developed to measure high-frequency current and voltage, close to electrode surfaces in inductive and capacitive etching chambers. Attenuating radio-frequency (RF) voltage probes are often used for voltage measurements in plasma chambers. However, at high frequencies over 50 MHz, the reading of RF voltage by these probes strongly depends on how the grounding wire is connected to a posited earth point. On the other hand, a voltage probe of the capacitive divider-type provides the voltage reading defined by the direction of dominant electric field, resulting in physically meaningful data even over 100 MHz. The latter approach is therefore taken. Since this voltage probe is designed with a high input impedance, the 50 ohm cable of an arbitrary length can be connected so as to place its sensing part in a small space of a chamber. Our current probe design is based on the pick-up coil approach. However, this current probe is designed to remove contamination of electric field from current reading. After precise calibration, both the probes can be mounted at any surface of the plasma etching chamber.

The probes are firstly used to monitor the etching uniformity in a capacitive plasma discharger operated at 162 MHz. The experimental concept is based on the electrical control methodology proposed by Sobolewski et al. (1999). Due to the 162 MHz standing wave built up in the transmission part of the chamber, the interpretation of current and voltage measurements is not so straight-forward. However, the voltage probe, mounted close to the wafer position shows better correlation with etching uniformity compared with another commercialized voltage probe mounted at the exit of the RF match box.

In the second experiment, these electrical probes are used to monitor the phase difference between two floating electrode in a capacitive discharging etching chamber. This experiment is aimed at testing the approach suggested by Bera et al. (2008). While experiments on uniformity-control via RF-phase was reported in the literature of Sung et al. (2009), one problem with these experiments is that the phase shift was monitored in the pre-match position. Unless special care is taken to characterize the match state, the phase change controlled by the phase-shifter would not have provided precise information on phase between the two electrodes. In our experimental set-up, this issue will be overcome by monitoring voltages close to the electrode surfaces.

These preliminary experiments indicate that these high-frequency voltage/current probes have a broad range of in-situ applications in the future design of etching chambers.

8:40am **PS2-TuM3 The Determination of Energy Fluxes in Plasma Surface Interaction**, ***H. Kersten***, University of Kiel, Germany **INVITED**

Since the thermal conditions at substrate surfaces affect essentially the interaction of elementary processes during plasma treatment of solid surfaces (deposition, etching, modification), the experimental determination of the energy influx from plasma to substrate is of great importance.

The total energy influx can be measured by special calorimetric sensors (thermal probes). One method is based on the determination of the temporal slope of the substrate surface temperature in the course of the plasma process. The heating curve as well as the cooling curve (after switching-off) are fitted by suitable functions and the time derivatives at same environmental temperature are calculated. By knowing the calibrated heat capacity of the sensor the difference of the time derivatives yields the integral energy influx to the surface. Simultaneously, the electrical current to the substrate can be obtained and by variation of the sensors bias voltage the energetic contribution of charge carriers can be determined. By using thermal probes of different materials it is even possible to verify the effect of surface recombination, secondary electron emission and sputtering in respect to the energy balance of a substrate in plasma processing. By comparison of the experiments with model assumptions on the involved plasma-surface mechanisms the different energetic contributions to the total energy influx can be separated.

The method will be demonstrated for various process plasmas, e.g. magnetron sputtering (HiPIMS), asymmetric rf-discharge, ion beam source, and ECR afterglow.

9:20am **PS2-TuM5 Noninvasive Electrical Monitoring of Ion Current, Ion Energy, Electron Temperature, and Electron Yield**, ***M.A. Sobolewski***, National Institute of Standards and Technology

Traditional plasma diagnostic techniques that require inserting a probe into a plasma are not compatible with commercial plasma reactors and the manufacturing environment. In contrast, the radio-frequency (rf) current and voltage across a discharge can easily be measured outside the reactor, without perturbing the plasma or process. Furthermore, the waveforms of rf current and voltage contain information about process-relevant plasma properties. For example, one technique [1,2] has been developed which uses a numerical model of the plasma and its sheaths to analyze the waveforms and determine from them the total ion current and ion energy distributions. This method, however, assumes that the electron temperature is constant, and it neglects any emission of electrons from the electrode or substrate surfaces. To investigate errors arising from these assumptions, variations in electron temperature were measured by a Langmuir probe during fluorocarbon plasma etching of silicon dioxide films, and values for the yield of ion-induced and photon-induced electron emission were estimated. These results allow the resulting uncertainties in ion current and ion energy to be quantified. They also provide tests of how well the existing technique can be extended to also provide monitoring of electron temperature and emitted electron yield, in addition to ion current and ion energy.

[1] M. A. Sobolewski, J. Vac. Sci. Technol. A 24, 1892 (2006).

[2] M. A. Sobolewski, J. Appl. Phys. 95, 4593 (2004).

9:40am **PS2-TuM6 Controllable Electron Beam for Optical Emission Studies in Real-Time Process Plasmas**, ***G. Padron-Wells****, *P.L.S. Thamban,* University of Texas at Dallas, *J. Hosch,* Verity Instruments, *M.J. Goeckner*, University of Texas at Dallas

Process control in etch plasma systems are often achieved by optical emission spectroscopy (OES) signals. One such application is etch endpoint

***** Coburn & Winters Student Award Finalist detection. In systems where plasma emissions are low, OES signals for process control cannot be employed. To address this problem, a versatile electron extraction method has been developed and used in conjunction with an OES diagnostic system to reliably measure changes in gas composition and emission cross sections for CF_4 plasma etch environments. An inductively coupled plasma source is employed to source electrons in an excitation region where optical emission measurements are conducted. Unique to this design is the control it offers to measure electron impact optical excitation of gas phase species. Cross section response for Argon emission lines with respect to electron beam energy correlates well with published data. Cross section behaviors for the strongest emission lines characterizing the CF_x molecular system are presented. Also, ability to detect 0.1% changes in feedstock gas chemical composition makes this design a highly sensitive end point detection system for analysis of semiconductor process chemistries. Work supported in part by NSF (Grant CBET- 0922962) and Verity Instruments.

10:40am **PS2-TuM9 A New Diagnostic Tool of Electron Energy Distribution Function in Capacitive Modes in High Frequency Plasmas**, *H. Shindo, **Y. Nakazaki***, Tokai University, Japan

A new diagnostic tool to measure Electron Energy Distribution Function (EEDF) by an emissive probe has been proposed[1] and applied to radio-frequency (RF) plasmas. In particular, the measurements are made in the capacitive mode which is occurred at the various frequencies of 2 to 60 MHz. It is generally difficult for a conventional probe method to measure EEDF in RF plasmas, because of the plasma potential fluctuation, particularly in the capacitive mode. On the contrary, one of the advantages of the present method is that the measurements are free from the high frequency potential fluctuation.

The method is based on measurement of the functional relationship between the floating potential change ΔV_F and the heating voltage V_H of emissive probe. If the Maxwellian plasma is concerned, the following equation can be obtained as a practical and useful formula.[1]

It is important to know that the value of ΔV_F contains information of electron energy distribution with several electron volt interval along the floating potential V_F, because ΔV_F is determined only by the current of plasma electrons with an energy interval.

In the experiments, the values of ΔV_F were measured in the Ar plasmas which were produced by a single-loop antenna[2] in the frequencies of 2 to 60 MHz and the gas pressures of 5 to 100 mTorr. The values of ΔV_F behave quite differently, depending on the frequency and the gas pressure, hence the plasma mode. It is found that the capacitive mode is appeared at the pressures below 20 mTorr at 2 MHz, 10 mTorr at 13 MHz, and at 60 MHz, the behavior of floating potential change ΔV_F is fairly complicated, hence non-Maxwellian plasma. In all capacitive modes, from the data set of ΔV_F and V_F, the electron energy probability function (EEPF) is calculated, and the EEPF thus obtained reveals a bi-Maxwellian with the two electron temperatures depending on the frequencies. For an example, the data set of ΔV_F and V_F at the pressures of 3 to 7 mTorr at 13 MHz revealed the high energy tail with the temperature of 3.0 to 5.0, while at 10 mTorr the EEPF showed a straight line, hence a Maxwellian. At 2 MHz, on the other hand, the capacitive mode was appeared even in higher RF power, but the two temperature mode was not so typical. It should be emphasized that the present diagnostic method becomes powerful in observation of the plasma mode transition in a variety of frequencies.

References:

[1] K.Kusaba and H.Shindo, Review of Scientific Instruments, **78**, 123503-1(2007).

[2] Y.Jinbo and H.Shindo, Applied Physics Express, **2**, 016001-1(2009).

11:00am **PS2-TuM10 Frequency Probe Measurements in Processing Plasmas**, ***D.R. Boris***, NRL/NRC Postdoctoral Research Associate, *S.G. Walton*, Naval Research Laboratory, *M. Baraket*, NRL/NRC Postdoctoral Research Associate, *E.H. Lock, R.F. Fernsler*, Naval Research Laboratory

Plasma density measurements are an essential tool in understanding and controlling processing plasmas across a wide range of applications. Charge collection probes (Langmuir probes) are of limited utility in depositing plasmas, high pressure applications or in processes that require the use of reactive gases, as these environments result in unreliable data acquisition. Plasma frequency probes are an attractive alternative to Langmuir probes in such applications since they do not suffer significant performance degradation in these environments. Frequency probes are capable of measuring plasma density over a range of 10^8 to 10^{12} cm^{-3} and, it is possible to extract the plasma potential and electron temperature. This presentation details the use of plasma frequency probes, in a variety of different geometries, to measure plasma parameters in unique systems, such as plasma produced by electron beams, operating at higher pressures, or in reactive gases (O_2 and SF_6). Where possible these measurements are compared with Langmuir probe measurements for identical experimental parameters.

11:20am **PS2-TuM11 Probe Geometry Induced Electron Energy Distribution Function (EEDF) Distortion**, ***A.E. El Saghir****, *E.M. Martin, S.S. Shannon*, North Carolina State University

One of the most valuable plasma characteristics that can be obtained from a Langmuir probe is the Electron Energy Distribution Function (EEDF). This is carried out by subtracting the ion contribution of the probe current, the shape of the electron current for probe potentials lower than the plasma potential is used to reconstruct the EEDF. The integral relationship for electron current in the transition region of a single probe voltage-current characteristic has been previously derived for planar probe configurations[1]. The Druyvesteyn relation for obtaining EEDF's from Langmuir probes is derived based on a model that assumes that only an electron's energy component perpendicular to the electric field generated by the biased probe determines whether an electron is collected or deflected by the probe when operating with an electron retarding potential. Cylindrical and spherical probe geometries have an additional electron retarding mechanism not accounted for in the Druyvesteyn relation. This additional mechanism comes in the form of a centrifugal retarding potential whose strength is determined by the initial angular momentum when the electrons are far away from the probe. In this work, formulations for cylindrical and spherical geometries are presented. These integral relationships are used to demonstrate the impact of ignoring probe geometry in EEDF extraction and highlights distortion of EEDF's when these geometric considerations are not taken into account. Finally, by combining the integral formulation for cylindrical and spherical probes with the analytical findings of Hoskinson for a finite cylindrical probe[2], we present a study of the effect of finite length cylindrical probe geometries on EEDF solutions.

[1]Druyvesteyn M.J, Z. Phys.,vol. 64,1930, pp. 781-798.

[2]R. Hoskinson, and N. Hershkowitz, Plasma Sources Sci. Technol. vol. **15,** 2006,pp. 85-90.

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11:40am **PS2-TuM12 How Fast do Ions Fall Out of a Two Ion Species Plasma? Experimental Test of a New Theory**, ***N. Hershkowitz***, *C.-S. Yip*, University of Wisconsin-Madison, *G. Severn*, University of San Diego

Recent experiments have shown that ions in weakly collisional plasmas containing two ion species of comparable densities nearly reach a common velocity at the sheath edge. A new theory suggests that collisional friction between the two ion species enhanced by two stream instability reduces the drift velocity of each ion species relative to each other near the sheath edge and finds that the difference in velocities at the sheath edge depends on the relative concentrations of the species. It is small when the concentrations are comparable and is large, with each species reaching its own Bohm velocity, when the relative concentration differences are large. To test these findings, ion drift velocities were measured near the near sheath edge in Argon-Xenon plasmas as a function of the concentration ratio using the laser-induced fluorescence technique. We show that the predictions are in good agreement with a revised version of the model. This is the first experimental test of the collisional friction model.

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