Thursday Morning, November 12, 2009

Plasma Science and Technology
Room: B2 - Session PS2-ThM

Plasma Sources
Moderator: J.-P. Booth, CNRS/Ecole Polytechnique, France

8:00am **PS2-ThM1 Power Dynamics in Low Pressure Capacitively Coupled Plasma Discharges**, ***S. Rauf***, *K. Bera, L. Dorf, K. Collins*, Applied Materials, Inc.

As feature sizes shrink and feature aspect ratios increase in advanced microelectronics devices, critical dielectric etching processes in capacitively coupled plasmas (CCP) are generally transitioning towards lower gas pressures (< 30 mTorr). Long electron mean free path and large bias voltages in this regime means that kinetic effects play an important role in the power dynamics in these low pressure plasma discharges. A coupled one-dimensional particle-in-cell (PIC) and fluid model is used to understand power dynamics in low pressure CCP discharges in this investigation. Our PIC model for charged species is based on the well-established computational techniques developed by Birdsall and colleagues (C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation*, IOP Publishing, Bristol, 1991) and includes a Monte Carlo based model for charged species collisions. Since multiple neutral species are present in plasmas of typical etching gases, the PIC model is coupled to a fluid model for neutral species that takes into account species transport in the plasma bulk, chemical reactions, and surface processes. The PIC + fluid model is applied to understanding power dynamics in a variety of etching-relevant single and dual frequency plasmas including Ar, O_2, and CF_4. Substantial fraction of applied power is consumed by the ions in the sheaths, which is dissipated at the electrodes. In Ar, electrons primarily gain energy at the sheath edge during sheath expansion, which results in highly energetic electrons. These energetic electrons stream through the plasma towards the opposite electrode, causing excitation, dissociation and ionization in their path. At low pressures (< 50 mTorr), these energetic electrons are able to reach the opposite sheath and lose some their energy while decelerating in the sheath. This behavior is consistent with the fact that plasma density is lower at lower pressure in the 5 – 50 mT range. The situation becomes more complicated in molecular gases due to electron collision processes with low threshold energies. Secondary electrons play an important role in sustaining the plasma at low frequencies (< 30 MHz), but sheath heating of electrons is sufficient for plasma sustenance at higher frequencies (> 60 MHz). Simulation results will be compared to experimentally measured ion densities.

8:20am **PS2-ThM2 Ballistic Electrons and Resulting EED*f* in a DC+RF Hybrid CCP Reactor**, ***L. Xu***, *L. Chen, M. Funk*, Tokyo Electron America

The DC+RF Hybrid is a capacitively coupled plasma (CCP) etcher with RF applied to the wafer electrode and a high-negative DC voltage on the opposite electrode 3cm away. Ion-secondary-electrons from the DC electrode are accelerated by the DC-sheath into the plasma as ballistic electrons. Gridded energy analyzers are placed behind the RF electrode for EED*f* measurements. Experiment's pressure-range varies from 30 mTorr to 70 mTorr with DC-voltage up to –1kV. EED*f* reveals, (1) Maxwellian bulk, (2) ballistic electrons with energy corresponding to the applied DC-voltage, (3) a continuum from Maxwellian to the ballistic electron peak, (4) middle-energy electrons with distinct energy-peak. Measured EED*f* qualitatively agree with PIC numerical experiment. The energy of the distinct middle-energy peak seems to depend on the sheath thickness and varies from ~ 40eV to 300eV. While ballistic electrons' finite collisions contribute to the continuum, other non-negligible channel such as Landau-damped e^--beam plasma waves, should be considered. The distinct middle-energy peak could result from Landau damping of a strong plasma wave of a specific wave number. The energy range of middle-energy peak is favorable in sustaining ionization, rendering the necessity of heating the Maxwellian bulk for a similar level of ionization.

8:40am **PS2-ThM3 Simulation of 450 mm Dual Freqeuncy Capacitively Coupled Plasma Tools: Conventional and Segmented Electrodes**, ***Y. Yang****, Iowa State University, *M.J. Kushner*, University of Michigan

Wafer diameters will soon transition from 300 mm to 450 mm at a time when excitation frequencies for capacitively coupled plasmas (CCPs) are increasing to 200 MHz or higher. Already for 300 mm tools, there is evidence that wave effects (i.e., propagation, constructive and destructive interference) affect the processing uniformity. The increase to 450 mm is likely to exacerbate these affects, perhaps requiring non-traditional tool designs. This is particularly important in dual frequency (DF) CCP tools in which there are potential interactions between frequencies. In this talk, we discuss results from a 2-dimensional modeling study of the plasma properties in 450 mm DF-CCP tools. To resolve wave and electrostatic effects, a full-wave Maxwell equation solver in the Hybrid Plasma Equipment Model is employed. To capture the high frequency heating, excitation rates are provided by spatially dependent electron energy distributions generated by a Monte Carlo simulation. A Monte Carlo simulation is also used to predict ion energy distributions as a function of radius on the substrate. Results will be discussed for plasma properties in DF-CCPs for low frequencies of ≤ 10 MHz and high frequencies up to 200 MHz, and gas pressures of < 10s mTorr. Segmented electrodes will be discussed as a means to suppress wave effects by making the electrical distance between the electrode feeds and the sheath edges as uniform as possible. The effects of tuning the lengths of the segments and the positions of rf feeds on plasma uniformity will be discussed.

*Work supported by the Semiconductor Research Corp., Tokyo Electron Ltd. and Applied Materials Inc.

9:00am **PS2-ThM4 A Scalable, VHF/UHF Compatible, Capacitively Coupled Plasma Source for Processing Large-Area Substrates at High Frequencies**, ***A.R. Ellingboe***, *D. O'Farrell, C. Gaman*, Dublin City University, Ireland, *F. Green, N. O'Hara, T. Michna*, Phive Plasma Technologies, Ireland

A recent trend in plasma etching and plasma enhanced CVD has been the increase in rf frequency used to sustain the plasma. For capacitively coupled plasma sources, increasing the rf frequency increases the fraction of power coupled into the electrons in comparison to ion energy gained in the sheath. The concept of 'high-frequency chemistry' is discussed, and some evidence that systems operated at hundreds of Megahertz have different electron kinetics have been presented (Samukawa, etal, J. Vac. Sci. Technol. A 17(5), Sep/Oct 1999, and D.O'Farrell, this conference).

However, the present trend to increase rf frequency is incompatible with increases in wafer size to 450mm and beyond.

No where is the evidence more clear than in PECVD of amorphous and microcrystalline Silicon for the photo-active layer in thin-film photovoltaic devices. Growth rates for these layers, while maintaining the necessary mechanical and electrical properties, can increase with increasing rf frequency, and in some cases yield superior film properties at the higher deposition rates (P.G. Hugger, etal, MRS 2008). However, in this industry substrate sizes are very large, exceeding 1m characteristic lengths, which puts substantial limits for a conventional plasma diode topology on using frequency as a control vector to increase deposition rate, thus increasing factory through-put and decreasing cost.

In this talk we will introduce a novel plasma source topology that enables increased rf frequencies on arbitrary size plasma source without causing wavelength effects. The concept is to segment the powered electrode into discrete tiles; For example as a checkerboard. Adjacent tiles can be powered out of phase with each other. In this way the displacement current coupled by one electrode is balance by and equal and opposite current of the adjacent electrode. Thus zero net current is coupled into the plasma, zero net current is coupled through the sheath above the substrate, and no wavelength effects occur even for substrates large in comparison to the rf wavelength.

Highlights of recent results in the operation and application of the plasma source to PECVD of silicon will be presented.

***** PSTD Coburn-Winters Student Award Finalist

9:20am **PS2-ThM5 Characteristics of Ferrite Enhanced Internal Linear Antenna for Large Area (2750mm x 2350mm) Inductively Coupled Plasma Source**, ***J.H. Lim**, K.N. Kim, G.H. Gweon, S.P. Hong, G.Y. Yeom*, Sungkyunkwan University, Korea

Inductively coupled plasmas sources (ICPs) have been applied to a variety of plasma processing including flat panel display processing (FPD) and semiconductor processing. Especially, for the FPD applications, to increase the inductive coupling to the plasma, internal-type antennas have been more intensively investigated.

In this study, the plasma characteristics of an internal-type linear ICP source having the size of 2750mm χ 2350mm installed with a Ni-Zn ferrite module was investigated. Especially, the effect of the Ni-Zn ferrite and different driving frequency of 2MHz and 13.56MHz on the plasma characteristics and electrical characteristics of the plasma source was investigated.

The results showed that, by the magnetic field enhancement using the ferrite, the operation of the antenna at 2MHz showed higher power transfer efficiency, lower antenna impedance, and lower rf rms voltage compared to that operated at 13.56MHz without the ferrite. For the ferrite enhanced ICP source operated at 7kW of 2MHz rf power, high density plasmas on the order of 2.0 x 10^{11}cm^{-3} could be obtained with 15mTorr Ar which was about two higher than that obtained for the source operated at 13.56MHz. When photoresist etch uniformity was measured by etching the phtoresist using 40mTorr Ar/O_2(7:3) mixture for the operation at 2MHz with the ferrite module, the etch uniformity of about 11% could be obtained.

9:40am **PS2-ThM6 Large-Scaled ECR Line Plasma Production by Microwave in a Narrowed Rectangular Waveguide**, ***H. Shindo**, Y. Kimura,* Tokai University, Japan*, T. Hirao*, Kochi Institute of Technology, Japan

Long line-shaped plasmas are inevitable in material processing in manufacturing industries, such as solar cell film CVD, flat panel displays (FPDs), and various surface modification of large-area thin films. In this work, a newly proposed method of large-scaled line plasma production is studied. In particular a long line ECR (Electron Cyclotron Resonance) plasma production is examined. In this method, microwave power of frequency of 2.45 GHz in a narrowed and flattened rectangular waveguide is employed to produce a long uniform ECR line plasma. Since the width of waveguide is very close to the cutoff condition, the wavelength of microwave inside the guide is very much lengthened, providing a condition of long line high density plasma with a great uniformity.

The narrowed rectangular wave-guide of 1.0 and 2.0 m in length and 5mm in height were prepared and the width of the waveguide is 62 mm which is very closed to the cut-off condition. The waveguide has a long slot on the top surface to launch the micro-wave into the discharge plasma chamber of 1.0 and 2.0 m in length. At the end of wave guide, a short plunger was quipped to adjust the phase of the standing microwave, hence the uniformity of the plasma thus produced. The magnetic field, which is generated by NdFeB magnet of 20 mm in thickness and 50 mm in width, is applied to plasma to produce the resonance field of 875 Gauss at the position of 10mm below the slot antenna. The plasmas of Ar at the pressures of 0.5 to 5Torr were produced by employing an extremely long microwave wavelength. The plasma thus produced was three-dimensionally measured by a Langmuir probe.

The electron density in the plasma thus produced showed a very high value, as high as 10^{12} cm^{-3} at the pressure of 0.5 Torr. In particular the cross sectional profile of the electron density showed a strong magnetic filed dependence and it becomes highest at the ECR resonance point, one order higher than in non-resonance region, indicating that the plasma production is due to the electron cyclotron resonance. The axial profile of electron density is quite good and the plasma uniformity was within 5 % in the entire plasma, indicating that the ECR line plasma is realized. It was also found that the profile of electron density was adjustable by the short plunger. To be specific, the electron density measured at a fixed Z position showed a standing wave-like profile, indicating the short plunger has a function of phase-shifter as expected. Thus we conclude that the present method of large-scaled ECR line plasma production is quite advantageous for large area processing.

10:40am **PS2-ThM9 PIC Simulations and Probe Measurements of the EEDF in a Microwave Surface-Wave Plasma Source**, ***R.V. Bravenec***, Fourth State Research, under contract to Tokyo Electron America, Inc.*, J.P. Zhao, L. Chen, M. Funk,* Tokyo Electron America, Inc.*, C.Z. Tian, K. Ishibashi, T. Nozawa*, Tokyo Electron Technology Development Institute, Japan

Microwave surface-wave plasma sources for wafer etching or deposition are promising alternatives to capacitively- or inductively-coupled sources. Unlike the latter, the source and wafer are decoupled, such that the wafer may be independently biased without affecting the source. Furthermore, microwave surface-wave sources are known to produce relatively dense, quiescent, low-temperature plasmas near the wafer surface, thereby minimizing wafer damage. Our device consists of an RLSA (radial line slot antenna) which transmits 2.45 GHz microwaves into a large quartz resonator disk which then couples to the plasma. We compare 2-D PIC (particle-in-cell) simulations from the VORPAL code[1] with Langmuir probe measurements[2] of the EEDF (electron energy distribution function) of the plasma. The simulations, a continuation of earlier work,[3] include ionization using a Monte-Carlo model with an energy-dependent cross section. Secondary emission from the quartz surface is modeled with energy and incident-angle dependent yield and produces a specific energy spectrum of outgoing particles. Fitting of the probe I-V curves employs a novel method of assuming from the outset two Maxwellian distributions plus a drifting Maxwellian to model a beam component. This method, unlike fitting the curves to polynomials or such, aids in interpretation of the results. We find that the EEDF near the resonator disk is typically dominated by the beam component, transitions to two Maxwellians away from the disk, then thermalizes to a single cold Maxwellian near the wafer surface. Simulations and data for various plasma densities and gas pressures will be presented.

[1]C. Nieter and J. R. Cary, J. Comp. Phys. **196**, 448 (2004).

[2]J. P. Zhao et al., poster at this conference

[3]R. V. Bravenec et al., poster at Gaseous Electronics Conference, Dallas, Oct., 2008.

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11:00am **PS2-ThM10 Characterization of an Expanding Chlorine Plasma Produced by an Electromagnetic Surface-Wave**, ***O. Boudreault**, S. Mattei,* Université de Montréal, Canada*, R. Khare,* University of Houston*, L. Stafford,* Université de Montréal, Canada*, V.M. Donnelly*, University of Houston

Plasmas produced by propagating surface waves have attracted attention because of their long and stable plasma columns without accompanying guiding structures. This is because the electric field supporting the discharge is provided by a traveling wave that carries the power away from the applicator, guided by the plasma column and the dielectric tube enclosing it. In long, narrow plasmas the wave-to-plasma power transfer is usually assumed to occur locally such that the axial density profile is determined by the wave attenuation coefficient. As a result the electron density, n_e, decreases in a quasi-linear manner along the plasma column in the direction of the wave propagation down to the critical density for surface wave propagation where the plasma decays abruptly (= expansion region) . At low pressures, however, the plasma tends to expand well beyond this critical point such that the description of the axial density distribution in terms of the local approximation is no longer valid. We investigated the influence of gas pressure on the spatial structure of a high-density chlorine plasma produced in a 6 mm, inside diameter, quartz tube by a propagating 2450 MHz surface wave. The axial variation of the electron density was determined from the spatial phase characteristics of the wave and the 828.0 nm emission line of Xe inserted as a tracer. As expected, n_e decreased linearly with axial position from the wave launcher, except in an expansion region near the end of the plasma column where the decrease of n_e was more abrupt. The thickness of this expansion region decreased with increasing pressure, going from about 8 cm at 5 mTorr to less than 1 cm at 100 mTorr. The Cl_2 percent dissociation obtained from the calibrated Cl_2(306 nm)-to-Xe emission ratio remained fairly constant except in the expansion region where it decreased sharply. For example, at 5 mTorr, the Cl_2 percent dissociation was 95 % near the wave launcher and 15 % at 2 cm from the end of the plasma column. While the expansion region showed a decrease in the electron density and Cl_2 percent dissociation, no noticeable change in the electron energy distribution function (EEDF) was observed. For all pressures and axial positions, the EEDF determined by trace-rare-gas-optical-emission-spectroscopy remained Maxwellian. The electron temperature (T_e) was fairly independent of the axial position, going from ~12 eV at 5 mTorr to ~2 eV at 100 mTorr. The high T_e values are due to a combination of high gas temperatures (T_g = 463 K at 5 mTorr and 635 K at 100 mTorr, measured by N_2 C->B emission rotational spectra) and small tube bore (0.6 cm), and are in good agreement with a global model.

11:20am **PS2-ThM11 Vacuum Ultraviolet Plasma Emission in a Capacitively-Coupled Dielectric Etch Reactor**, ***E.A. Hudson**, M. Moravej, M. Block, S. Sirard, D. Wei, K. Takeshita,* Lam Research Corp.*, B. Jinnai, S. Samukawa*, Tohoku University, Japan

Plasma optical emission in the visible and ultraviolet (UV) ranges is widely used to characterize the properties of thin-film processing plasmas. Emission in the vacuum ultraviolet (VUV) range is less commonly detected due to the challenges of eliminating air from the optical path. However the interaction of VUV radiation with the substrate may be important in plasma processing, particularly for device damage and for the modification of sensitive materials such as low-k dielectrics and 193nm photoresist. To improve the understanding of these mechanisms, a windowless optical system was incorporated onto a commercial capacitively-coupled confined-plasma dielectric etch reactor. VUV and UV emission spectra in the 40 – 230nm range were measured for a range of plasma conditions, including simple single-gas plasmas and more complex etching plasmas. The spectra showed a strong dependence on gas chemistry, due to the characteristic emission lines associated with the plasma atomic and molecular composition. More importantly, the frequency of plasma electrical excitation was found to influence the VUV spectra. Correlations were observed between plasma emission in specific wavelength ranges and process-induced low-k dielectric damage.

11:40am **PS2-ThM12 Damage-Free, Uniform and High-Target-Utilization Novel Magnetron Sputtering Plasma Source by Rotating Helical Magnet**, ***T. Goto,*** Tohoku University, Japan, *N. Seki, T. Matsuoka,* Tokyo Electron Technology Development Institute, Inc., Japan, *T. Ohmi*, Tohoku University, Japan

Novel magnetron sputtering equipment, called rotation magnet sputtering (ROT-MS), is being developed to overcome various disadvantages of current magnetron sputtering equipment. Disadvantages include:(1) very low target utilization of less than 20%, (2) difficulty in obtaining uniform deposition on the substrate, and (3) charge-up damages and ion-bombardment-induced damages resulting from very high electron temperature and that the substrate is set at the plasma-excitation region. In ROT-MS, a number of moving high-density plasma loops are excited on the long rectangular flat target surface by rotating helical magnets, and the deposition is performed by passing the substrate through this deposition region, resulting in very high target utilization with uniform target erosion and uniform deposition on the substrate due to time-averaging effect. T his excellent performance can be principally maintained even as equipment size increases for very large-substrate deposition. Plasma characteristics and deposition performances were investigated using ROT-MS equipment for both 8-inch wafer and 200-mm-square substrate. Deposition uniformity on 8-inch wafers for pure Al deposition results in that the film-thickness uniformity (defined by standard deviation divided by average thickness) is 0.5～2.5% in the wide pressure range from 0.33 to 5.3 Pa for the cases without any optimization of slit width configuration. The target utilization is estimated to be 59.7% from the measurement of the target erosion distribution. It is found that the target erosion distribution experimentally observed agrees well with the theoretical calculation. We have calculated target utilization for various helical magnet configurations, and revealed that very high target utilization larger than 90% is feasible. Detailed ion current distributions at the substrate were measured by measuring ion saturation currents flowing to the multipoint probes set at the stage (in this measurement, the helical magnet is not rotating). The results show that the distribution is uniform within the slit area for the rf-excited plasma case with the order of 1 mA/cm^2, while the distribution of the magnetic filed loop pattern is observed with the order of 0.1 mA/cm^2 for the dc-excited case. Because strong horizontal magnetic fields (>0.05 T) are produced within a very limited region just at the target surface, very low electron-temperature plasmas (< 2.5 eV for Ar plasma, and < 1 eV for direct-current-excited Xe plasma) are excited at the very limited region adjacent to the target surface for charge-up damage-free and ion-bombardment-induced damage-free processes.

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