Plasma Science and Technology
Room: 306 - Session PS2-WeA

Plasma Diagnostics, Sensors, and Control I
Moderator: J.P. Booth, Lam Research Corporation

1:40pm **PS2-WeA1 Novel On-Wafer RF-Current Sensor: Sheath Impedance and Plasma Density**, ***M.J. Titus***, *D.B. Graves*, University of California, Berkeley

"On-wafer" plasma sensors are new metrology tools that provide spatially-resolved wafer-state and/or plasma information. Measuring the temporal and spatial evolution of wafer-surface and adjacent plasma characteristics is the key to developing advanced plasma tool control schemes. One such commercially available sensor is the PlasmaVolt™ device, developed by KLA-Tencor. We utilize a 150 mm diameter version of the commercial product consisting of an on-board electronics module with wireless communication that allows data storage of 2 RF-current sensors embedded on the wafer at different radial positions. We report results using this device in an inductively coupled plasma with RF-biased substrate under a range of conditions. Electron density and temperature are independently measured above the wafer using a Langmuir probe and the positive ion current to chamber walls is measured with a shielded planar probe. The RF-voltage and current waveforms applied to the substrate are measured with a digital oscilloscope. The quantitative relation between the PlasmaVolt™ sensor wafer measurement and the adjacent electron density is established using a fluid sheath model. We demonstrate with this combined experimental-modeling approach that the plasma density scales with the RF-current sensor measurements but the nature of the scaling is dependent on the sheath impedance. When the sheath impedance is predominately capacitive (corresponding to relatively low electron density and high RF-bias voltage) sensor measurements are proportional to the square-root of the electron density. When sheath impedance is more resistive (corresponding to relatively high electron density and low RF-bias voltage), the sensor measurement is proportional to electron density.

2:00pm **PS2-WeA2 In-situ Diagnostic to Measure Charging During Plasma Etching**, ***E. Ritz***, *M.J. Neumann, J.A. Hoban, D.N. Ruzic*, University of Illinois at Urbana-Champaign

In plasma etching processes, especially those with high aspect ratios, it is known that defects can occur such as trenching, bowing, and twisting. These defects are particularly noteworthy in the manufacture of DRAM deep-trench capacitors. In order to investigate the role of charging on these phenomena an in-situ diagnostic was fabricated using photolithographic and deposition techniques. The device consists of alternating layers of conducting and insulating materials. During the construction of the device, vias are integrated into the layout, extending all the way from the top surface to the substrate. The insulating layers create discrete measurement layers, provided by the conducting layers (electrodes). The electrodes are attached to voltage measurement leads and can then be used to measure the build up of sidewall charging at different heights along the via when exposed to a plasma. To determine the effect of geometry, if any, on charging, several aspect ratios were used by maintaining the same device thickness but varying the diameter of the vias. The entire stack is less than one micron thick, with vias ranging in diameter from 1 micron to 100 nanometers, thereby producing aspect ratios of 1:1 to 10:1. In addition, a macroscopic parallel to the diagnostic was constructed in order to compare how overall size of the features affects the charging properties. The macroscopic device is on the order of 1cm thick with features on the order of 1mm in diameter. The transition from macroscopic to microscopic gives a better understanding of the transport and charging phenomena involved in constructing DRAM features and at what scale they are significant. Conducting layers for the macroscopic device are metal and the insulating layers are ceramic. Plasma and charging experiments were conducted in a commercial silicon dioxide etch chamber. Typical ion fluxes measured on the order of 10^{17} ions/cm^2*sec. At 500W of 2.0 and 2.2 MHz power on each of the coils (1000W total), a plasma density of $2*10^{12}$ +/- $5*10^{11}$ cm^{-3} and electron temperature of 3 +/- 0.3eV was measured at 0.3+/-0.2 mm about the substrate at 4.5+/-1 cm from the edge of a 20cm chuck. RF variations in the signal were observed at the two driving frequencies and at the beating frequency of 150kHz, as expected. Results from the diagnostics will be shown for various plasma conditions and compositions.

2:20pm **PS2-WeA3 Time Dependence of Charge-Build-up Voltages in Production Etcher by On-Wafer Real Time Monitoring System**, ***J. Hashimoto***, *T. Tatsumi, S. Kawada, N. Kuriyama*, Miyagi Oki Electric Co., Ltd., Japan, *I. Kurachi*, Oki Electric Industry Co., Ltd., Japan, *S. Samukawa*, Tohoku University, Japan

Charge-build-up during plasma etching process is one of crucial issues to realize nano-scale devices. Because gate insulator thickness of such devices is shrunk down to 1nm range, the gate insulator breakdown caused by the charge-build-up is a key issue and has to be solved. To understand the phenomenon of the charge-build-up, it is absolutely necessary to monitor the time dependence of charge-build-up precisely. We have advanced charge-build-up monitoring sensors proposed by Dr.Samukawa. We have monitored etching parameters dependency and aspect ratio dependency in steady status in production etcher and have demonstrated effectiveness of the sensors. However, it was difficult to monitor charge-build-up phenomenon in unsteady status in detail. Therefore, we developed On-Wafer Real Time Monitoring System which can measure the data of charge-build-up voltages at the timing of several micron seconds and can record charge-build-up voltages in processing in production etcher. In general, the recipes in production etchers have several sequential etching steps. Unstable plasma tends to occur especially at the time of chucking wafer electro-statically, turning on-off plasma discharge and switching the etching step. As a result, they induce plasma damages. Therefore, it is important to monitor charge-build-up voltages not only in steady status, but also in unsteady status. In this study, we monitor the time dependence of charge-build-up voltages in processing in production etcher by On-Wafer Real Time Monitoring System and the charge-build-up phenomena in unsteady status will be discussed in detail in the presentation.

2:40pm **PS2-WeA4 Origin of Electrical Endpoint Signals in Rf-biased, Inductively Coupled Plasma Etching**, ***M.A. Sobolewski***, *D.L. Lahr*, National Institute of Standards and Technology

When a plasma etch consumes one layer and exposes an underlying layer, changes are detected in measured electrical parameters, such as the dc self-bias voltage and the voltage, current, impedance, and phase at the fundamental and harmonic frequencies. Consequently, these electrical signals are widely used for endpoint detection, i.e., for determining when to terminate an etch. However, the mechanisms responsible for the observed electrical changes are not well understood. The electrical changes may indicate a change in plasma electron density and ion flux caused by changes in the gas-phase densities of etch products and reactants that occur as an etch proceeds to completion. Alternatively, changes in substrate electrical properties or surface properties such as work function and the yield of secondary and photoemitted electrons may be involved. To investigate these mechanisms, experiments were performed in an inductively coupled plasma reactor equipped with rf bias and a wave cutoff probe. The cutoff probe[1,2] allowed small changes in the plasma electron density to be measured with good accuracy and resolution, on a time scale of a few seconds, regardless of the presence or absence of insulating layers on probe surfaces. Simultaneous measurements of electrical signals and cutoff probe data were made during CF_4/Ar plasma etches of thermal silicon dioxide films on silicon substrates. Changes observed in the components of voltage, current, impedance and phase at the rf bias frequency were related to, and fully explained by, changes in plasma electron density measured by the cutoff probe. The dc self-bias voltage and harmonic signals showed more complicated behavior that cannot be explained solely by changes in plasma electron density. The results allow several general conclusions to be drawn about the relative reliability and usefulness of endpoints obtained from each of the different electrical signals.

[1] M. A. Sobolewski and J.-H. Kim, J. Appl. Phys. 102, 113302 (2007).
[2] J.-H. Kim, S.-C. Choi, Y.-H. Shin and K.-H. Chung, Rev. Sci. Instrum. 75, 2706 (2004).

3:00pm **PS2-WeA5 Local and Non-Local Changes of Plasma Parameters in an Expanding Thermal Plasma Reactor Coupled with a Pulse-Shape Substrate Biasing Technique**, ***P. Kudlacek***, *R.F. Rumphorst, M. Creatore, M.C.M. van de Sanden*, Eindhoven University of Technology, The Netherlands

The control of the flux and energy of ions bombarding the substrate is crucial to enhance deposited film properties or etch rate at, for example, low substrate temperatures or in weak remote plasmas. The most widespread method for these purposes is biasing because of its simplicity and suitability for operation with both conductive (dc bias) and dielectric (rf or pulsed bias) substrate. Recently, pulsed bias became subject of increased interest mainly due to lower and controllable heat load of the sample and, considering that rf bias inherently leads to bimodal energy distribution of ions bombarding the biased substrate (IED), also a promising technique to reach narrow almost unimodal IED. When pulse-shaped bias voltage is connected to the substrate holder the sheath rebuilding at the beginning of on-pulse and the ion-induced secondary electron emission during the pulse can lead to production of significant amount of fast electrons which can non-locally affect the plasma and near-wall sheath potential as has been reported by Demidov at al. (2005 Phys. Rev. Lett. 95 215002). Therefore, an effect of local and non-local changes of plasma parameters in a reactor with substrate holder biased by pulse-shaped voltage was studied in this work. Non-local changes are discussed on the basis of the electron temperature T_e and ion density n_i which are determined spatially using a double Langmuir probe technique, while the distribution function of ions bombarding the biased substrate shows local effects of biasing such as additional generation of ions driven by bias voltage and influence of collisions. IEDs are measured by means of a retarding field energy analyzer. Two limit biasing conditions are presented for comparison, namely dc bias and 13.56 MHz rf bias which shows practically no and strong (e.g. almost 5 times higher T_e in the distance of 30cm from the biased substrate holder) non-local plasma parameters affection, respectively. All experiments were run in a remote expanding thermal plasma (ETP) reactor, in Ar and Ar/N_2 gas mixture compositions under several pressures (up to 35 Pa). The substrate holder was negatively biased (up to -300V) by means of a home designed pulsed power supply operating with a frequency of up to 200 kHz and a variable duty cycle.

4:00pm **PS2-WeA8 Plasma Diagnostics by a Coaxial Resonant Cavity**, ***S. Kobayashi***, Applied Materials Inc.

Microwave plasma diagnostics were developed mainly in the field of microwave and plasma interaction. Recently, these methods have also been adopted for plasma dischargers. The main advantages of microwave diagnostics are; (a) the capability to measure directly a plasma electron density and, (b) the applicability in a process gas environment. Intended to use in dischargers, new devices (e.g. plasma absorption probe, U-shape probe, plasma microwave interferometer) were developed based on the microwave method in the last decade. However, when these open structural probes are used in a small chamber, radiation from the probe surface cannot be neglected, resulting in random resonances caused by interference with a chamber wall. To resolve this issue, a coaxial resonant cavity is developed, which is open for plasma diffusion, while it is closed with respect to microwave radiation. In vacuum, the cavity is designed to have a sharp resonance in a 2-4 GHz band. When plasma is generated in a chamber, the resonant frequency up-shifts due to a change in the effective dielectric constant. Once the resonant frequency is given as a function of a loaded electron density, the electron density is measured by monitoring a frequency-shift. Preliminary measurements of electron plasma density of Argon and Nitrogen showed good agreements with those of a Langmuir probe. Theoretically, this probe can measure the electron temperature of a plasma, since the electron temperature can be represented as a function of variation in the quality factor of a resonance in the cavity. This possibility will be also studied and discussed in the paper.

4:20pm **PS2-WeA9 On Detection and Prevention of Plasma Instabilities**, ***V.L. Brouk***, *D.C. Carter, R.L. Heckman*, Advanced Energy Industries, Inc.

The presence of instabilities in low pressure (5 to 100 mT) electronegative plasmas is well documented. In inductively driven plasmas instabilities often exist between the stable low density, capacitive mode and the stable high density, inductive regions causing oscillations in particle density, optical emission and coil voltage. Instabilities also occur in capacitively coupled plasmas driven similarly by electron attachment to electronegative species. Oscillation frequency can range from less than a 100 Hz to greater than 10 kHz and can depend on multiple process parameters including pressure, gas flow, gas mixture and power level.[1,2] Especially for high efficiency, switch mode power amplifiers, interaction between the power-dependent plasma impedance and the load-dependent amplifier response can promote or aggravate unstable behavior. This interaction involves complex impedance trajectories having both magnitude and angle components when displayed in the impedance plane. The common practice of adjusting transmission cable length shifts the phase angle of the amplifier portion of the interaction and thus minimizes the combined feedback to achieve a stable operating state. For a singular set of conditions, the point of transition from one mode to the next can be well defined and effectively addressed in this manner. But complete mapping of such behaviors across a broad process space is not practical due to the enormous number of variables present in modern plasma processes. Further, adjustments of physical cable length can be problematic in many applications. For these reasons a convenient means for predicting the onset of plasma instabilities and ideally a method for avoiding an unwanted transition to unstable operation is desirable. In this study we demonstrate a quantitative diagnostic for assessment of plasma stability providing a measure of margin from an unstable threshold. When used with a properly equipped RF amplifier, the technique provides context necessary to avoid the onset of instability in these plasmas. Using a fixed transmission cable and minor adjustments in RF frequency to adjust the electrical wavelength, we show how this method can be used to actively stabilize both low and high frequency plasma oscillations.

[1] A. M. Marakhtanov, et. al., J. Vac. Sci. Technol. A 21 (6), Nov/Dec 2003, 1849-1864.
[2] A. Descoeudres, et. al., Plasma Sources Sci. Technol. 12 (2003), 152–157.

5:00pm **PS2-WeA11 Secondary RF Plasma Assisted Closed-Field Dual Magnetron Sputtering System for ITO Thin Film Deposition on Plastic Surfaces**, ***L. Meng****, *R. Raju,* University of Illinois at Urbana-Champaign, *T. Dockstader,* Kurt J Lesker Company, *H. Shin, D.N. Ruzic*, University of Illinois at Urbana-Champaign

Since the demand keeps growing for larger size plasma displays, and for inexpensive flexible displays on plastic or other organic substrates, it is important to develop a plasma processing device to handle large size substrates, while maintain the uniformity and quality of deposited materials without damaging the substrate. An RF plasma-assisted closed-field dual magnetron sputtering system investigated in this study is the prototype of such a system. The prototype consists of two 3 inch DC magnetrons which can be operated at both balanced and un-balanced (closed-field) configurations. This system enhances the plasma density, metal ionization fraction and has the ability to produce high quality films at lower substrate temperature. An RF coil was fabricated, installed in between the magnetrons to initiate secondary plasma. A RF compensated Langmuir probe was used to diagnose the spatial distribution of argon sputtering plasma. In the constant current mode (50 mA) of the magnetrons, the RF plasma enhances the electron density to one-order of magnitude higher compared with no RF plasma and results in an increase in the deposition rate. The ionization fraction of the sputtered materials was measured using the QCM combined with electrostatic filters. The presence of RF plasma effectively enhanced the ionization fraction of the sputtered metal flux to about 90%. The performance of the closed-field magnetron configuration was compared with the balanced one. Enhancement in the electron density is observed in the closed-field magnetron configuration near the substrate which is twice as large compared to the balanced one. Experiments were conducted on the deposition of ITO on glass and plastic substrates at closed-field configuration. Wide range of operating parameters has been investigated to get highly transparent and conducting films. ITO thin film with 91% of transparency and resistivity of 30 Ω/square was obtained at the magnetron current of 90 mA, pressure of 5 mTorr, 2.5% of O_2 fraction in Ar, the RF power of 225 W, and substrate temperature was well kept below 120 °C. Results on the optimization of the operating parameters for high quality ITO film will be presented. Surface morphological studies have been carried out on the film using both balanced and un-balanced configurations. Results from extending this system to larger rectangular shaped magnetrons in a real flat panel display manufacturing system will also be presented.

5:20pm **PS2-WeA12 Optical and Electrical Diagnostics of an Arc Plasma Jet under Atmospheric Pressure**, ***C.Y. Wu***, National Taiwan University, *C.W. Chen, W.C. Cheng,* Industrial Technology Research Institute, Taiwan, *C.C. Hsu*, National Taiwan University

An arc plasma jet under atmospheric pressure was studied. This plasma jet is able to generate stable plasma sustained by a DC pulsed power of 20 kHz ~ 40 kHz using nitrogen and clean dry air. A voltage probe and a current probe were used to characterize the voltage and current waveform of this plasma jet. The optical emission at this plasma jet downstream was monitored by an optical emission spectrometer. Multiple thermocouples were used to measure the downstream jet temperature. The current and voltage waveforms showed glow-to-arc-transition-like characteristics. It is found that the time-averaged current increases with the power input and is not sensitive to the flow rate. The peak current, however, increases as the applied power decreases and as the flow rate increases. The peak current remains below 1.0 A under high power and low flow rate conditions while reaches 3.0 A for low power and high flow operation regimes. It suggests that the peak current is not directly controlled by the amount of power input to the plasma. Optical diagnostics shows nitrogen molecular emissions dominate in nitrogen plasma jets. The nitrogen plasma jet temperature appears to be higher than the temperature of the air plasma jet as measured by the thermocouples at the jet downstream. The detailed discharge mechanism will be presented and its implications in materials processing will be discussed.

* PSTD Coburn-Winters Student Award Finalist

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