Friday Morning, November 17, 2006

Plasma Science and Technology
Room 2011 - Session PS2-FrM

Diagnostics

Moderator: G.A. Hebner, Sandia National Laboratories

8:00am **PS2-FrM1 Substrate Temperature Sensor Measurements and Analysis in an Inductively Coupled Plasma***, C.C. Hsu,* ***M.J. Titus****, D.B. Graves,* University of California at Berkeley

The OnWafer commercial plasma sensor system consists of sensors embedded on a thin-film battery-powered Si wafer that can enter and exit commercial plasma tools via conventional wafer-handling robotic transfer. An on-board electronics module coupled with wireless communication allows storage of process data followed by infrared uploading post-process. While this is a proven avenue for plasma process development and quasi-real time process control applications, full interpretation of sensor measurements in terms of intrinsic plasma characteristics requires validation. This talk describes the use of the OnWafer system in a university-built inductively coupled plasma (ICP) tool, equipped with a variety of plasma sensors. We describe results from a combined plasma and wafer model and compare the model predictions to both sensor measurements and plasma measurements. Measurements of wafer temperature transients (using PlasmaTemp@super TM@) are compared to a wafer and plasma model. A combination of radially-resolved Langmuir probe measurements and an ICP model is used to obtain the radial energy flux profile from the plasma to the wafer surface. Model predictions and measured transient wafer temperature profiles agree near-quantitatively, if details of the wafer and chuck characteristics are properly included. The model and measurements must include the effects of heat release due to ion-electron recombination and radical recombination at the wafer surface.

8:40am **PS2-FrM3 In-Situ Characterization of Oxygen Plasma Surface Etching by Infrared-Visible Sum Frequency Spectroscopy***,* ***D. Farrow****, G.A. Hebner, E.V. Barnat,* Sandia National Laboratories

Unlike many other techniques used to characterize surfaces under plasma exposure, Infrared-visible sum frequency (IVSF) generation is a surface specific probe molecular vibrations that can be carried in situ to follow molecular interactions and plasma initiated chemistry at the interface in quasi real time. We present an in-situ characterization of octadecyltrimethoxysilane monolayers on Quartz in the presence of DC oxygen plasma based on hydrocarbon lines in the IVSF spectra as a function of plasma exposure time, voltage and oxygen pressure. These will be correlated with ellipsometry and infrared absorption measurements of samples under equivalent conditions. This test system will be used to demonstrate the unique advantages and limitations of IVSF in plasma systems.

9:00am **PS2-FrM4 Application of In Situ Plasma Analysis on Deep Trench Plasma Etch Hardware Design and Process Development***, S. Wege, A. Steinbach, S. Barth, A. Henke, J. Sobe,* Qimonda, Dresden, Germany*;* ***M. Reinicke****, J.-W. Bartha,* Dresden University of Technology, Germany*; G.D. Stancu, N. Lang, J. Roepke,* Institute of Low Temperature Plasma Physics, Germany

Facing critical dimensions below 60nm requires significantly improved knowledge about the complex process mechanisms. In situ plasma analysis has been performed on different dual frequency capacitively coupled MERIE plasma reactors for DRAM technology development. High aspect ratio silicon etching mechanisms are investigated as a function of tool parameters for HBr, NF3, as well as HBr/O2/NF3 electronegative plasmas. Plasma analysis includes investigation of the influence of different plasma coupling on process results using an extensive set of planar Si and SiO2 etch rate experiments, feedstock etch gas dissociation studies, and further energy analysis of different etch species for a plasma and surface chemistry model using an in situ mass and energy plasma analyzer. For the first time, online concentration monitoring of etch species using Quantum Cascade Laser Absorption Spectroscopy is performed. Measurement results are used to extend the knowledge and insight of experimental plasma process conditions, and further as input parameters for simulations of conditions in plasma bulk and sheath, as well as structure development on wafer surface. A combined application of plasma analysis, simulation and process development on product wafers is an efficient way to optimize chamber hardware and process conditions, and to support process development.

9:20am **PS2-FrM5 2D-t Plasma Image during One Bias Period of a 2f-CCP in Ar by Emission CT***,* ***T. Ohmori****, T. Kitajima, T. Makabe,* Keio University, Japan

It has been required to maintain the radial uniformity of the ion velocity distribution incident on an oxide wafer biased deeply by a LF source in a 2f-CCP. The ion velocity distribution synchronized with the sheath dynamics in front of the biased wafer is one of the critical internal plasma parameters further to control and optimize the etching profile in the next generation of the technology having an allowance within several nm. In our previous paper, we have performed a design of the functional separation in a 2f-CCP. High density plasma is sustained at a VHF (100 MHz) source, while the high energy ions are produced by a LF (500 kHz) bias source without additional discharge. We have experimentally investigated the temporal image at the central z-axis @LAMBDA@(z, t; r = 0) and at the radial position at fixed z @LAMBDA@(r, t; z), and the time-averaged image in the 2D space @LAMBDA@(r, z) in a 2f-CCP by using the CT of the optical emission from the short-lived Ar(2p@sub 1@) and Ar+(4p@super 4@D@sub 7/2@) as a probe of the plasma structure and the transport of the secondary electrons.@footnote 1@ In this work, we reconstruct an automatic CT system for the detection of the line integral of the emission in the entire space of the reactor, and demonstrate the temporal change of the 2D image @LAMBDA@(z, r, t) in a full gap of 20 mm of parallel plates during one cycle of the bias in a 2f-CCP at 25 mTor in Ar. In particular, we focus on the profile of the sheath-bulk edge and of the electrode-wall interaction as a function of bias phase in the results of the 2D-t images. @FootnoteText@ @footnote 1@T. Kitajima, Y. Takeo, N. Nakano, and T. Makabe, J. Appl. Phys. 84, 5928(1998). T. Kitajima, Y. Takeo, and T. Makabe J. Vac. Sci. Technol. A 17, 2510 (1999).

9:40am **PS2-FrM6 Advanced Plasma Sources for the Next-Generation Processing***,* ***H.-Y. Chang****, S.-H. Seo,* Korea Advanced Institute of Technology (KAIST) **INVITED**

As the feature sizes of devices have shrunk in recent plasma processing, plasma sources operating at low pressures (1-100mTorr) have been required for formation of good anisotropic patterns, high throughput, and damage-free process. Recently, the main subjects in developing a new plasma source have been the attainment of good uniformity in large area, the control of plasma parameters for the process optimization, and the development of new application area. Among several plasma sources, inductively coupled plasma (ICP), capacitively coupled plasma (CCP) and the ultra low electron temperature plasma sources have been the focus of keen interest as the new and efficient sources for many plasma processing including the semiconductor manufacturing because these have many attractive aspects such as their simple apparatus, relatively efficient plasma generation, good special uniformity, low and independently controlled ion energy, and scalability to large-area plasma sources.@footnote 1@ In this presentation, a couple of newly developing plasma sources will be introduced with the brief review of the electron heating mechanisms in plasma sources along with the recent experimental and theoretical results focusing on the electron energy distribution function (EEDF), ion energy distribution function(IEDF) and rf fields in the collisionless regime.@footnote 2,3@ In addition, some examples for the control of plasma parameters through adjusting rf frequency and power, operating pressure, gas mixing ratio,@footnote 4@ and other external parameters in order to optimize the process will be presented. @FootnoteText@@footnote 1@ S.H.Seo, C.W. Chung and H.Y.Chang: Surf and Coating Tech. 131(2000) 1-11 @footnote 2@ V.A.Godyak : Plasma Sources Sci. Technol. 3,169(1994) @footnote 3@ C.W.Chung and H.Y.Chang : Phys.Rev.Lett. @footnote 4@ K.H.Bai and H.Y .Chang: Physics of Plasma

10:20am **PS2-FrM8 Real-time, Noninvasive Monitoring of Ion Energy and Ion Current at Insulating Electrodes***,* ***M.A. Sobolewski****,* National Institute of Standards and Technology

The dc self bias voltage is often monitored during plasma processing because it provides a rough estimate of ion bombardment energies. However, many industrial plasma reactors are now equipped with electrostatic chucks, which have a large dc impedance that makes dc bias measurements impossible. A chuck may also have a large rf impedance which produces a significant rf voltage drop across the chuck. In this study chuck impedance effects were investigated in an inductively coupled plasma reactor by incorporating insulating structures into the rf-biased lower electrode. Measurement methods were developed to characterize the capacitive impedance of the insulating electrode itself and the combined impedance of the electrode plus the wafer. This impedance was included in a numerical model of the plasma and its sheaths, and the combined model was used to analyze measured rf bias current and voltage waveforms. This approach allows a real-time, noninvasive monitoring technique developed for bare metallic electrodes@footnote 1,2@ to be extended to insulating electrodes, including electrostatic chucks. The technique not only determines the dc self bias voltage present on the surface of the wafer or chuck, but also the time-dependent plasma potential and sheath voltages, the total ion current, and the ion energy distributions at the wafer or chuck surface. @FootnoteText@ @footnote 1@ M. A. Sobolewski, J. Appl. Phys. 95, 4593 (2004). @footnote 2@ M. A. Sobolewski, J. Appl. Phys. 97, 033301 (2005).

10:40am **PS2-FrM9 The Ion Energy Distributions in a High Power Impulse Magnetron Discharge*, J. Bohlmark,*** Chemfilt Ionsputtering AB, Sweden*; M. Lattemann,* Linköping Univ., Sweden*; J.T. Gudmundsson,* Univ. of Iceland, Iceland*; A.P. Ehiasarian,* Sheffield Hallam Univ., UK*; Y.A. Gonzalvo,* Hiden Analytical Ltd., UK*; J. Carlsson,* Chemfilt Ionsputtering AB, Sweden*; N. Brenning,* Royal Institute of Tech., Sweden*; D. Lundin, U. Helmersson,* Linköping Univ., Sweden

We report on the ion energy distributions of sputtered and ionized Ti and the sputtering gas (Ar and N2) for a high power impulse magnetron sputtering (HIPIMS) discharge. High power pulses were applied to a conventional planar circular magnetron Ti target. The peak power on the target surface was 1-2 kW/cm@super 2@ with a duty factor of about 0.5 %. Time resolved, and time averaged ion energy distributions were recorded with an energy resolving quadrupole mass spectrometer. The ion energy distributions are very broad during the active phase of the discharge with maximum detected energy of 100 eV, but quickly narrows as the pulse is switched off. The time averaged measurements show that about 50 % of the Ti ions have energies over 20 eV. The broad nature of the distributions together with the fact that the Ti and gas ion distributions peak at different energies during the active phase of the discharge excludes acceleration between the plasma potential and the grounded spectrometer as explanation for the energetic ions. Instead we suggest that the shape of the distributions can be explained by a combination of a strong pressure increase in front of the target and ion acceleration by electric field instabilities. The composition of the ion flux was also determined, and reveals a high metal fraction. During the most intense moment of the discharge, the ionic flux consisted of approximately 50 % Ti1+, 24 % Ti2+, 23 % Ar1+, and 3 % Ar2+ ions. We are planning to continue the study by investigating the effect of the energetic plasma on thin film growth. It is expected that HIPIMS can be used as a tool for film densification where a substrate bias is not easily applied, which opens up for improved device or component performances.

11:00am **PS2-FrM10 Monitoring of Electron Density in Plasma Reactor with Frequency Shift Probe*, K. Nakamura,*** Chubu University, Japan*; H. Sugai,* Nagoya University, Japan

A plane type of frequency shift (FS) probe for monitoring electron density in reactive plasmas was developed with modification of the hairpin probe.@footnote 1@ The FS probe is connected to a network analyzer to detect reflection from the probing plane antenna located at an inner surface of the chamber. The reflection becomes minimum at a certain frequency due to resonance at the antenna, and the resonant frequency shifts from f0 for vacuum without plasma to higher frequency f in the presence of the plasma because of a decrease in permittivity. The frequency blue shift (f-f@sub 0@) gives the absolute electron density ne according to ne (x10@super 10@cm@super -3@) =[f@super 2@-f@sub 0@@super 2@]/0.81 in unit of GHz for f and f@sub 0@. In principle, the FS probe is based on volume wave resonance while a previouly-proposed surface wave (SW) probe relies on surface wave resonance.@footnote 2@ In comparison to the SW probe, the plane FS probe has various advantages. The FS probe can be installed on a reactor wall surface, thus minimizing the disturbance to processing plasmas. Furthermore, since the resonance cavity of the FS probe is formed at the plane antenna itself, the resonance frequency can be measured easily in a wide range of the discharge conditions. The characteristics of FS probe were examined in an ICP reactor as functions of the RF power and the discharge pressure, and the experiments revealed that the wall-installed FS probe could monitor relative variations of electron densities in the bulk plasma.@FootnoteText@ @footnote 1@ R. B. Piejak et al. J. Appl. Phys. 95 (2004) 3785.@footnote 2@ H. Kokura et al: Jpn. J. Appl. Phys. 38 (1999) 5262.

11:20am **PS2-FrM11 Energy Distribution and Flux of Fast Neutrals and Residual Ions Extracted out of High Aspect-Ratio Holes in a Neutral Beam Source*, A. Ranjan,*** *V.M. Donnelly, D.J. Economou,* University of Houston

The energy distribution and flux of fast neutrals and residual ions extracted from a neutral beam source were measured. Positive ions generated in an inductively coupled argon plasma were extracted through a metal grid with high aspect ratio holes. Ions suffering grazing angle collisions with the inside surface of the grid holes turned into fast neutrals. The neutral energy distribution shifted to lower energies compared to the corresponding residual ion energy distribution. The neutralization efficiency increased with power, decreased with the imposed plasma potential (controlled with a boundary voltage) and, for thin neutralization grids, was almost independent of plasma gas pressure. The residual ion flux decreased with increasing hole diameter and hole aspect ratio. The fast neutral flux first increased and then dropped as the hole diameter was increased. These results were explained based on plasma molding inside the grid holes. The effect of surface roughness of the grid walls on the energy distribution and flux of fast neutrals and residual ions was also studied. A nearly atomically smooth grid was fabricated from a closely-spaced stack of polished Si (100) wafer strips. With this grid, a small fraction of fast neutrals was observed at energies nearly equal to the maximum ion energy. For the metal grids, with rougher surfaces, the highest energy neutrals were well below the maximum ion energy. These observations will be discussed in terms of the type of scattering (specular vs. non-specular) that occurs when ions are converted into fast neutrals.

11:40am **PS2-FrM12 Electron Energy Distribution Function Measurement in Radio-Frequency Plasmas Produced in Insulated Vessels*, H. Shindo,*** *K. Kusaba,* Tokai University, Japan

A new method to measure electron energy by an emissive probe has been proposed. The method is based on measurement of the functional relationship of the floating potential and the heating voltage of emissive probe. From the measured data of the floating potential change as a function of the heating voltage, the curve of the probe collection current-voltage can be analytically obtained. The present method has several important advantages of the following: (1) it is even applicable to radio-frequency plasma in which the potentials are usually fluctuating, (2) also applicable to plasmas which are produced in non-conductive containers. One of key issues in the method is to achieve a perfect floating condition for radio-frequency. Then, the probe circuit was optically connected into the measurement circuit. In the experiment, the emissive probe 30 micrometer diameter tungsten was heated by 40 kHz pulse voltage, and the floating potential at the heating voltage off period and the floating potential difference between the heating off and on period were measured by digital oscilloscope in argon plasma. The measurements were made in both the capacitively coupled and inductively coupled plasmas. It was shown that the plasma electron energy probability function could be obtained without any RF compensating circuit even in capacitively coupled plasmas. In particular, since the method is very sensitive near the plasma potential, the clear indication for the depletion of the low energy electron could be obtained. This low energy electron depletion is due to high plasma potential. Therefore, in the inductively coupled plasma this low energy electron depletion was obtained near the induction antenna, but at the further positions from the antenna the energy distribution became Maxwellian. This feature has also been reported recently. This change in the electron energy distribution found in ICP was very systematic with the gas pressures and the distances from the antenna.

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