## Plasma Science and Technology
## Room: Aztec - Session PS-WeM

## Plasma Surface Interactions (Fundamentals & Applications) I
**Moderator:** M. Hori, Nagoya University, Japan

8:00am **PS-WeM1 On the Mechanism of Plasma Surface Interactions in Electron Beam-Generated Plasma in Nitrogen Environment**, ***E.H. Lock***, *S.G. Walton, R.F. Fernsler*, Naval Research Laboratory

There are numerous features of electron beam-generated plasmas that distinguish them from discharges. In particular, most of the electron beam energy is spent on gas ionization (≈ 50 %), some on gas dissociation and very small amount on excitation. Thus, less radicals and photons are produced in electron beam-generated plasmas compared to discharges. Moreover, the electron temperature is low (< 1eV) so that the plasma potential is low and therefore the energy of the ions (1-5 eV) that attack the surface is low. These low ion energies minimize the undesirable physical sputtering and ion-assisted chemical etching of polymer surfaces, thereby limiting changes to the polymer *surface morphology* and the *depth of modification*. Despite these differences, the chemical structure of the polymer surface exposed to electron beam plasma is changed. In this work, we focus on understanding the mechanism of plasma induced polystyrene modification in nitrogen through a careful analysis of the functional groups formed and their distribution with depth.

This work was supported by the Office of Naval Research.

8:20am **PS-WeM2 Breakthrough of Compatibility between Bowing-free Profile and Bottom CD in High Aspect Ratio Dielectric Etch Using DC Superimposed Capacitively-Coupled Plasma**, ***A. Nakagawa***, *H. Mochiki, M. Dojun, K. Yatsuda, S. Okamoto*, Tokyo Electron AT Limited, Japan

Fabrication of latest DRAM capacitor structure requires precise etch profile control of silicon dioxide due to the continuous trend of narrowing pitch and high aspect ratio (HAR) features. While a number of issues are recognized such as twisting and bottom distortion, bowing became an outstanding subject for DRAM technology development for its complexity to cope with the bottom CD; even slight bowing leads to interference with the adjoining structures, and adjustment of process conditions frequently accompanies decreased bottom CD. In the present report we explore the effect of DC superimposition in capacitively-coupled plasma (CCP) as a countermeasure, taking advantage of its controllability on necking level at the mask facet.

Generally speaking, bowing is induced by the reflected ions at the mask facet attacking silicon dioxide sidewalls. Moreover, shrunk mask entrance interferes with incident radicals to transfer to the hole bottom, narrowing its size. One of the solutions utilizes high ion energy, but our results demonstrated a strong correlation between mask necking and bottom CD, thus the evaluation focused on optimization of mask necking.

Next, observation of deposition at the silicon dioxide sidewall varied with process parameters lead to systematic understandings of its physical amount and local enhancement, as well as the declining behavior at the removal process. By means of process parameters, the necking degree of the mask opening was controlled and the relationship among necking, bowing and bottom CD was examined.

As a result, it is necessary to improve necking at mask opening to minimize bowing and to keep bottom CD simultaneously. Optimization of process parameters enables etch profile enhancement by dispersing necking location, which normally decreases selectivity to mask. However, DC-superimposed CCP facilitated maintaining selectivity to mask with preferable etch profile, and less bowing with sufficient bottom CD.

8:40am **PS-WeM3 High Resolution Cryogenic Silicon Etch Process Development for Nanoscale Trenches**, ***Y. Wu***, Oxford Instruments, Lawrence Berkeley National Laboratory, *D. Olynick*, Lawrence Berkeley National Laboratory, *A. Goodyear*, Oxford Instruments, *C. Peroz*, Abeam Technologies, *S. Dhuey, X. Liang, S. Cabrini*, Lawrence Berkeley National Laboratory

We present work on the development of a cryogenic silicon etch process suitable for etching shallow and high aspect ratio nanoscale features below 50 nm for use in nanophotonics applications. With shrinking feature sizes, profile and critical dimension control tolerance is reduced and appropriate processes must be developed. Cryogenic silicon etching using $SF_6$-$O_2$ offers several advantages over fluorocarbon or heavier halogen based processes. For example, low bias voltages can be used, reducing mask erosion and ion damage. In addition, the etching process is not purely ion dependent which reduces some of the problems at small feature sizes associated with the ion angular distribution and ion interaction with the sidewall which can cause less than ideal profiles. Furthermore, sidewall contamination is minimal eliminating critical dimension (CD) variations due to etch residue cleaning. Two challenges to creating a suitable cryogenic $SF_6$-$O_2$ process for 50-100 nm features and below, is optimizing the passivant to eliminate undercut and reducing the etch rate enough to control the process. Furthermore, an etch process which changes in time accordingly to the etch depth and aspect ratio may be necessary for features below 20 nm.

The cryogenic $SF_6$-$O_2$ based silicon etching process was investigated in an Oxford Instruments ICP 380 using a L18 Taguchi design of experiments (DOE) matrix. For the DOE, trench type features sized 300-500 nm are investigated. Parameters varied include pressure, temperature, RF power, ICP power, He backing pressure, and oxygen content. The effects on the etch rate, selectivity, profile angle, and surface roughness were examined. The process was then finely tuned for etching of densely packed silicon trenches ranging from 100 to 10 nm. These features are patterned both with electron beam lithography and nano-imprint lithography techniques. Resist selectivity is high in both cases: from 10:1 to 20:1. Vertical and smooth sidewalls were obtained . Etched patterns were used to create nanophotonic devices such as nanospectrometers and laser waveguides and imprint masks for high resolution applications.

9:00am **PS-WeM4 Quantitative Analysis and Modeling of Dry Etch Induced Physical Damage in Si Surface Layer**, ***J.H. Yoon***, *W.S. Kim, J.W. Han, D.H. Kim, J.Y. Lee, K.S. Shin, C.J. Kang*, Samsung Electronics, Republic of Korea

As the size of memory cell is scaled down, due to the structural limitation of planar transistor, new structural device is needed, like a recessed channel or FinFET. When using the etch process for a new structure patterning, however, exposure of Si surfaces to a reactive plasma can result physical damages. These effects lead to degradation of electrical properties of silicon substrates. Therefore, it is necessary to identify the measurable damage and then to design for reducing physical damage and/or removing the damaged layers without any further damage. In this study, using SRIM(Stopping and Range of Ions in Matter), we simulate ion distribution and damage region in the Silicon with etch species and Vdc, and using TEM, SE(Spectro Ellipsometry), RBS (Rutherford backscattering spectroscopy), we analyze the physical thickness of the damaged layer that depends on etch condition (Ion energy, selectivity to Si). In order to quantify the damage of exposed Silicon surface by etch process, the amount of defect was electrically calculated, respectively for Si/SiO2 interface and Silicon bulk defect, using the charge pumping and gate controlled diode pattern at the MOSFET TEG. We found that defect density of high ion energy and high selectivity condition is bigger over a few order than low energy and low selectivity condition. In the latter case, the ion penetration depth is shallower and even damaged layer was also simultaneously etched during the process, but, in the former case, highly damaged layer was formed in the early stage of plasma exposure and defects were accumulated by increasing exposure time. To remove the damaged layers, normally we're using the light etch as post etch treatment. That is very effective to remove in case of highly damaged surface, but, in case of low damaged Silicon surface, light etch itself increase the amount of damage. So we have to choose well controlled treatment process with the degree of damage for improving the properties of Silicon substrate. The obtained results enable us to predict the etching induced physical damage to the devices in advance at the stage of plasma etch process design.

9:20am **PS-WeM5 On the Role of CF in Fluorocarbon Plasmas: Gas-Phase Reactions and Surface Interactions**, ***M.F. Cuddy***, *E.R. Fisher*, Colorado State University

A complete understanding of the nature of fluorocarbon (FC) plasma systems necessarily includes a description of $CF_x$ species behavior, including CF, $CF_2$, and $CF_3$. Our current research focuses primarily on understanding the gas-phase properties and reactions and gas-surface interactions of CF molecules produced from sparsely polymerizing $CF_4$ and $C_2F_6$ plasmas. An enriched understanding of these systems can elucidate the mechanisms contributing to film growth and may pave the way for enhanced plasma deposition and etching applications. To this end, we have employed laser induced fluorescence spectroscopy (LIF) and optical emission spectroscopy (OES) to probe the gas-phase behavior of CF, including calculations of rotational and vibrational temperatures. From these analyses, we determine that CF rotational states equilibrate with the plasma gas temperature at around 300 K. In addition, time-resolved actinometry has been employed to investigate gas-phase kinetics of the CF molecule as well as other $CF_x$ species in a range of FC systems. We have also extended the LIF studies to our unique imaging of radicals interacting with surfaces (IRIS) technique which probes the gas-surface interface during plasma processing. CF species exhibit a surface gain in density, with surface scattering coefficients greater than unity for Si and $ZrO_2$ substrates, indicating production of the molecule at film-passivated surfaces. For comparison, IRIS results for $CF_2$ in the same plasmas will also be discussed. Surface analyses by high-resolution x-ray photoelectron spectroscopy (XPS) and variable angle spectroscopic ellipsometry along with the gas-phase data have culminated in a proposed mechanism for gas-surface interactions of these molecules during plasma processing of Si and $ZrO_2$ whereby the contributions of both CF and $CF_2$ molecules to film formation is summarily developed.

9:40am **PS-WeM6 "Designer" Ion Energy Distributions on Substrates Immersed in a Plasma**, ***P. Diomede***, *D.J. Economou, V.M. Donnelly*, University of Houston

The energy of ions bombarding the substrate is critical in plasma etching (and deposition) of thin films. In conventional plasma processing, employing a sinusoidal substrate electrode voltage, the ion energy distribution (IED) is often very broad. However, as film dimensions approach the atomic level, control of the IED becomes critical. For example, selectivity considerations often dictate a narrow IED with a specified peak energy. In this work, semi-analytical models and particle-in-cell (PIC) simulations are employed to achieve "designer" IEDs, i.e., distributions with a desired shape and energy spread. This is accomplished by applying tailored voltage waveforms on the substrate electrode (spike, staircase, judiciously distorted square wave, etc.). Such waveforms can provide, for example, nearly mono-energetic IEDs or other desired shapes. Semi-analytic model results are compared with those of PIC simulation to identify the range of validity of the semi-analytic model. Predicted IEDs are also compared with experimental data under both collisional and collisionless sheath conditions. Strategies to control the energy flux of bombarding ions or to distribute the total energy flux to different energies will also be discussed.

Work supported by DoE Plasma Science Center and NSF.

10:40am **PS-WeM9 Modeling of Plasma-Induced Damage and Its Impacts on Parameter Variations in Advanced Electronic Devices**, ***K. Eriguchi***, Kyoto University, Japan **INVITED**

With scaling of advanced electronic devices, plasma-induced damage (PID) has been investigated extensively from various viewpoints. Although suppressing PID is one of the critical issues in plasma process optimization, there have been few reports which correlate the plasma parameters to device performance in terms of PID.

This study discusses one of the PID mechanisms, physical damage induced by ion bombardment on Si surface. We propose a new comprehensive framework linking an ion energy and the distribution function to device parameters, i.e., a unified PID design.[1)] The framework is based on a modified range theory[2)] and an analytical device-degradation model.[3),4)] To verify the validity, we performed both experiments to clarify the damaged-layer structures (the thickness, defect site density, and the electrical properties) by novel techniques[5)] and simulations (molecular dynamics and device simulations) to understand the quantitative effects.

We demonstrate prediction of performance degradation in metal-oxide-semiconductor field-effect transistors (MOSFETs) damaged by an inductively coupled plasma reactor which can apply the bias with two different frequencies (400 kHz and 13.56 MHz). The model prediction indicates that, in typical etching processes, the damaged-layer thickness can be determined primarily by an average self-dc-bias voltage rather than applied bias frequencies. This implication is found to be in good agreement with experimental results. Moreover, one can estimate also variation in device parameters from basic plasma parameters. Thus, it is concluded that the proposed framework is a key concept for future process and device designs.

1)K. Eriguchi et al., IEDM Tech. Dig. (2008) 443.

2)K. Eriguchi et al., to be published in Jpn. J. Appl. Phys., 2010.

3)K. Eriguchi et al., Proc. Symp. Dry Process (2009) 267.

4)K. Eriguchi et al., IEEE Electron Device Lett. 30, 1275 (2009).

5)K. Eriguchi et al., Jpn. J. Appl. Phys. 47 (2008) 2446.

11:20am **PS-WeM11 Time Resolved Diagnostics of a Pulsed Dual-Source Inductively Coupled Plasma**, ***H. Shin***, *W. Zhu, X. Lin, V.M. Donnelly, D.J. Economou*, University of Houston

A novel dual-source inductively coupled plasma (ICP) system was designed and built to control the electron energy distribution function (EEDF) in the plasma, and the ion energy distribution (IED) on the substrate. The main ICP source has a Faraday shield to minimize the RF component of the plasma potential. The substrate electrode, as well as a "boundary" electrode in contact with the plasma, can be independently biased by DC or RF voltages, of the desired waveform, to influence the IED. A secondary tandem ICP source can inject plasma, radicals or metastable atoms to the main ICP to influence the EEDF. The main ICP source was characterized using a Langmuir probe (LP), trace rare gas optical emission spectroscopy (TRG-OES), and an electrostatic ion energy analyzer. Emphasis was placed on pulsed plasma operation to achieve better control of the IED (as well as the ion angular distribution). With the Faraday shield installed, the plasma potential was several volts lower, and the peak-to-peak RF voltage of the plasma potential was suppressed to 1-2 V, as compared to the case without Faraday shield, allowing for smaller spread of the IED. The plasma potential, and thus the peak of the IED could be precisely controlled by the voltage applied to the boundary electrode. Accurate control of the ion energy and width of the IED is important for processes such as atomic layer etching, for which the threshold energies between etching and sputtering differ by only several volts. During the OFF period of a square wave modulation of the plasma power (50 μs ON, 50 μs OFF), the electron temperature decayed from 3.1 eV to less than 0.25 eV, with only a 20 % drop in plasma density for a 10 mtorr pressure, 200 W (average) power argon plasma. Time resolved EEDFs were also measured by the LP and compared to those extracted from TRG-OES experiments during the ON and first few ms of the OFF time. Tailored voltage waveforms were used to obtain "designer" ion energy distributions on the substrate. Finally, results for other gases (such as krypton and oxygen) will be discussed and compared to those obtained for argon plasmas.

Work supported by the DoE Plasma Science Center and NSF

11:40am **PS-WeM12 Investigations on Physical Processes for Low Temperature Plasma Activated Wafer Bonding**, ***T. Plach***, *K.H. Hingerl*, University of Linz, Austria, *D.V. Dragoi, G.M. Mittendorfer, W.M. Wimplinger*, EV Group, Austria

Direct wafer bonding is a "simple" method of directly connecting wafers, with suitable (in terms of micro-roughness and flatness) surfaces, permanently to each other, by bringing them into contact and subsequently annealing them. The conventional process for hydrophilic oxidized Silicon surfaces (native as well as thermal oxide) is well understood, and explained the following way:

Up to 100°C the substrate surfaces are held together via van der Waals interaction which is mediated by a few monolayers of water. In the range of 100-200°C the water diffuses away from the interface both along the interface and through the oxide into the crystalline bulk, where it reacts with the silicon and forms oxide. The increase of the bond strength from 50% to 100% of Si bulk strength is usually attributed to a closing of gaps at the interface [1], which starts at the softening temperature of the thermal oxide at around 850-900°C.

Low temperature plasma activated direct wafer bonding for a pair of native oxide – thermal oxide interfaces is a process that lowers the required annealing temperatures necessary for reaching high bond strength. Bulk strength can be realized by plasma activation with subsequent annealing at 300°C. At this temperature conventional wafer bonding reaches half of Si bulk strength, and is limited by gaps at the bonding interface. The mechanism behind this improvement compared to the non activated process is still under discussion.

To clarify the mechanism for this commercially available process, different bonding experiments were performed to evaluate the lifetime of the surface activation and the achievable bond strength when using substrates with various orientations. Interfaces of bonded wafer pairs were investigated by transmission electron microscopy (TEM). TEM images clearly show that there is no discernible interface between the native oxide on one side and the thermal oxide on the other side.

By covering half of the wafer during plasma activation, comparisons between the activated and non-activated region could be made by atomic force microscopy, by spectroscopic ellipsometry, by Auger analysis and by X-ray photoelectron spectroscopy.

It was found that the top surface stoichiometry is chemically changed, which favors bonding. Finally a model for the mechanism that explains the experimental results will be presented.

[1] Q.-Y. Tong, U. Gösele, *Semiconductor Wafer Bonding: Science and Technology,* Wiley, (1998)

# Authors Index

## Bold page numbers indicate the presenter