Monday Morning, November 2, 1998

The Science of Micro-Electro-Mechanical Systems Topical Conference

Room 324/325 - Session MM+PS-MoM

MEMS Processing and Deep Si Etch Technology

Moderator: L.M. Miller, Jet Propulsion Laboratory

8:20am **MM+PS-MoM1 Overcoming Barriers to MEMS Prototyping and Production**, ***D.A. Koester***, *K.W. Markus,* MCNC **INVITED**

As MEMS continues to grow and expand into new markets, there continues to be a need for low cost proof-of-concept and prototype fabrication. For the past 6 years, MCNC has provided a number of services designed to provide the domestic MEMS community with an array of fabrication and design services intended to help overcome the cost and accessibility barriers to MEMS product development. The cornerstone of this DARPA-supported program, called the MEMS Technology Network (TechNet), is the Multi-User MEMS Processes (MUMPs). MUMPs is a three-polysilicon surface micromachining process offered in a multi-user environment to offset the high cost of fabrication. Since its inception in January '92, MUMPs has fabricated over 1000 designs for more than 140 different R&D groups and has been available to the world-wide community since July of '98. The SmartMUMPS program enables electronics integration of MUMPs by way of flip chip of a standard ASIC designed with a variety of sensing blocks. LIGA technology is also made available through the program. The MEMS Technology Network also provides a spectrum of custom services to the community including deep silicon RIE, backside patterning, stock substrates and access to a Microcosm MEMCAD 4.0 seat.

9:00am **MM+PS-MoM3 Materials, Process, and Integration Issues in SiC MEMS**, ***M. Mehregany***, Case Western Reserve University **INVITED**

SiC MEMS technology holds great promise for applications which are characterized by presence of harsh environments (e.g., high temperatures, large number of vibrational cycles, erosive flows, and corrosive media). Historically, SiC research has focused on the materials and processes needed for high-temperature and high-power microelectronics. These devices require high-quality single crystal films and substrates, which lead most researchers to use 6H-SiC, since nearly defect-free wafers and epitaxial films are available. Unfortunately, high quality comes at a high price; 6H-SiC wafers are very expensive and are available only in small wafer diameters. Thus, applications for 6H-SiC devices are limited to areas which can absorb such high costs, such as (military) aircraft and spacecraft. Our work has been motivated by the necessity to develop a low-cost SiC MEMS technology to penetrate a much more diverse set of markets, including for example automotive. Additionally, we have been motivated to leverage off of the latest fabrication process technologies available from Si to push the SiC MEMS technology further, faster. As a result, we have pursued large-area substrates, i.e., 3C-SiC on Si. Unlike 6H-SiC, 3C-SiC is the only SiC polytype which can be heteroepitaxially grown on Si substrates. Heteroepitaxy on Si gives 3C-SiC a distinct advantage over 6H-SiC in terms of batch fabrication, since high quality, large-area Si substrates are readily available and comparatively very inexpensive. We have pursued the development of bulk and surface micromachining processes using 3C-SiC and poly-SiC, respectively. Heteroepitaxy of 3C-SiC on Si is attractive to MEMS not only for batch fabrication, but also for bulk micromachining. In fact, SiC is undoubtedly an excellent etch stop material for Si bulk micromachining, since Si anisotropic etchants such as KOH and EDP are impervious to SiC. We have used Si bulk micromachining techniques to fabricate a multitude of 3C-SiC structures, ranging from diaphragms for mechanical properties studies, pressure sensors, and optical transmission windows, to cantilever beams and torsional micromechanical structures. Bulk micromachining of 6H-SiC has been demonstrated by others, however the process is much more complicated and the dimensional control and etch stop capabilities are limited at this time. Unlike electronics applications which require high-quality single crystal films, MEMS is much more flexible in that structures can be fabricated from polycrystalline films. SiC MEMS is no exception. We have developed poly-SiC as a basic structural material for SiC MEMS. We have deposited APCVD poly-SiC films atop polysilicon and silicon dioxide sacrificial films on 4 inch diameter Si wafers. We have demonstrated SiC surface micromachining processes, and these have been used to fabricate the first SiC lateral resonant structures. These devices tested at temperatures up to 900C outperformed polysilicon resonators of like geometry with respect to high temperature capability. Of course, the surface micromachining technology using poly-SiC would be extendable to 6H- and 4H-SiC substrate technology, as well as integration with SiC electronics on these substrates. An overview of materials, process, and integration issues in SiC MEMS will be presented, including current device examples.

9:40am **MM+PS-MoM5 Thermally-Actuated Micro-Beam for Large In-Plane Mechanical Deflections**, ***E.S. Kolesar***, *P.B. Allen, J.T. Howard, J.W. Wilken,* Texas Christian University

Numerous electrically-driven microactuators have been investigated for positioning individual elements in microelectromechanical systems (MEMS). The most common modes of actuation are electrostatic, magnetostatic, piezoelectric and thermal expansion. Unfortunately, the forces produced by electrostatic and magnetostatic actuators tend to be small, and to achieve large displacements, it is necessary to either apply a large voltage or operate the devices in a resonant mode. On the other hand, piezoelectric and thermal expansion actuators can be configured to produce large forces and large displacements. Unfortunately, piezoelectric materials are not routinely supported in the fabrication processes offered by commercial MEMS foundries. Consequently, these limitations have focused attention on thermally-actuated devices for generating the large forces and displacements frequently required to position and assemble complex MEMS. This research focuses on the design, finite element analysis and experimental performance evaluation of a MEMS thermally-actuated beam. The motivation is to present a unified description of the behavior of the thermal beam so that it can be adapted to a variety of applications in the microsensor and microactuator arenas. A MEMS polysilicon thermally-actuated beam uses resistive (Joule) heating to generate thermal expansion and movement. When current is passed through the actuator from anchor-to-anchor, the larger current density in the released "hot" arm causes it to heat and expand more than the "cold" arm. Since both arms are joined at their free (released) ends, the actuator tip is forced to move in an arc-like pattern. Removing the current from the device allows it to return to its equilibrium state. To be a useful MEMS device, a thermally-actuated beam will need to produce incremental in-plane mechanical beam tip deflections that span 0-10 microns while generating force magnitudes greater than 10 micro-newtons. The thermally-actuated beam design was accomplished with the L-Edit software program, and the devices were fabricated using the Multi-User Microelectromechanical Systems (MEMS) Process (MUMPs) foundry at the Microelectronics Center of North Carolina (MCNC). A finite element modeling analysis was accomplished with the IntelliCAD computer program. This CAD software incorporates an MCNC fabrication process description file that generates a 3-D solid model of the thermal beam. Additionally, the thermal and electromechanical finite element analyses predicted beam tip deflections and forces consistent with experimental observations. When the "hot" arm's temperature is 600@degree@C (Joule heating), the resulting beam tip deflection is 4.55 microns. For a beam tip force of 14 micro-newtons, the displacement was calculated to be 12.9 microns. The resonant frequency, without damping, was calculated to be 74.7 kHz. The MEMS thermally-actuated beam performance was also experimentally characterized. When the drive voltage was varied between 0 and 8 VDC, tip deflections spanning 0-7 microns were observed. The corresponding tip forces spanned 0-12 micro-newtons. The resonant frequency in ambient air was 68.7 kHz. A measure of the reliability of the thermal beam was established to be greater than 2 million cycles, when continuously operated with a 60 Hz, 4-volt amplitude square wave.

10:00am **MM+PS-MoM6 Development of a Micro EHD Pump Using Laser Micro-machining**, ***C.C. Wong***, *D. Chu, D.R. Adkins,* Sandia National Laboratories

At Sandia, we are developing an active cooling MEMS device for microelectronics applications. This integrated device will incorporate a micro-pump, temperature sensors, micro-channels, and heat exchanger components into a single unit. The first step of this development is to rapidly prototype a micro-pump based on electro-hydrodynamic (EHD) injection principle using laser micro-machining technology. Two initial micro-pumps designs have examined for full fabrication. The first design has two silicon parts stacked vertically on top of each other. Gold is deposited on one side of each stacked plate to serve as electrodes for the electro-hydrodynamic pumping. A Nd:YAG laser is used to drill an array of circular holes in the "well" region of both silicon parts, leaving an open pathway for fluid movement. The Nd:YAG laser is preferred for our fabrication process than excimer laser because of a smaller up-front cost and a less potential environment, safety, and health concern with toxic gases when using excimer laser. Moreover the Nd:YAG laser will allow the operational wavelength to be converted to several frequencies from the

near infrared portion of the spectra (1064 nm @lambda@) to the ultraviolet portion of the spectra (266 nm @lambda@). After the holes are drilled, the silicon parts are aligned and bonded together with polyimide, thus becoming a EHD pump. Fluid flow has been observed when an electric voltage is applied across the electrodes. The newest design has the silicon parts which contain the flow grid oriented "back-to-back" and bonded together. This "back-to-back" design has a shorter grid distance between the anode and cathode plates so that a smaller voltage is required for pumping. A thinned Si spacer was used to maintain consistent grid distance between plates. Experimental results have demonstrated that this EHD micro-pump can generate a pressure head of about 287 Pa with an applied voltage of 120 V. @FootnoteText@ This work was supported by the US DOE under Contract DE-AC04-94AL85000.

10:20am **MM+PS-MoM7 Laminated Plastic Microfluidic Components for Biological and Chemical Systems**, ***P.M. Martin***, *D.W. Matson, W.D. Bennett, D.J. Hammerstrom,* Battelle Pacific Northwest National Laboratory

Laminated plastic microfluidic components are being developed for biological testing systems and chemical sensors. Applications include a DNA thermal cycler, DNA analytical systems, electrophoretic flow systems, dialysis systems, blood sampling, and metal sensors for ground water. This paper describes fabrication processes developed for these plastic microscale components. Most of the components have a stacked architecture, the fluid flows, or is pumped through as many as nine laminated functional levels. Functions include mixing, reaction, and detector channels, reservoirs, and detector electronics. Polyimide, PMMA, and polycarbonate materials with thicknesses between 25 and 100 µm are used to construct the components. This makes the components low cost, inert to many biological fluids and chemicals, and disposable. The components are fabricated by excimer laser micromachining the microchannel patterns and microstructures in the various laminates. In some cases, micropumps are integrated into these components to move the fluids. Vias and interconnects are also cut by the laser, and integrated with micropumps. The laminates are sealed and bonded by adhesive and thermal processes, and are leak tight. The parts withstand pressures as high as 790 kPa. Typical channel widths were 50 µm to 100 µm, with aspect ratios near 5. Performance data will be presented for the DNA thermal cycler and a voltammic chromium metal sensor.

10:40am **MM+PS-MoM8 Deep Anisotropic Etching of Silicon**, ***S. Aachboun***, *P. Ranson,* University of Orleans, CNRS, France

Dry etching of silicon has been largely studied in HDP reactors for many applications such as in Microelectronics. Moreover, deep etching is a relatively new approach that can be widely used in MEMS in the near future. However, as required depths increase, the etch rate and the anisotropy decrease radically with the Aspect Ratio (width/depth). We are interested in etching very deep anisotropic trenches (~100µm) with high Aspect Ratios (~50) and high etch rates (~5µm/mn). A HDP Helicon reactor using a SF6/O2 chemistry and a cryogenic chuck has been used for etching very narrow trenches and holes from 1,2µm to 10µm of width on n-type Si wafers with a SiO2 mask. The first results of this investigation show significant features that demonstrate the feasabilty of this method. Two microns width trenches have been etched over a depth of 50µm at 3µm/mn . The resulting profiles are highly anisotropic and the selectivity Si/SiO2 is over 500. A DOE has been set in order to evaluate the effects of the different parameters and, in order to monitor the plasma and improve the features, Langmuir probe, optical spectrometer and mass spectrometer investigations are planned.

11:00am **MM+PS-MoM9 Application of the Footing Effect in the Microfabrication of Self-Aligned, Free-Standing Structures**, ***A.A. Ayon***, *K. Ishihara, R. Braff, H. Sawin, M.A. Schmidt,* Massachusetts Institute of Technology

The footing or notching effect is observed when dry etching silicon or polysilicon layers on buried dielectric films.@footnote 1@ This effect is usually considered an undesirable feature for most applications, although it is frequently small in conventional reactive ion etching (RIE) tools due to the low density of the plasmas utilized. However, with the new generation of inductively coupled plasma etching tools the notching effect can extend laterally several microns depending not only on operating conditions but also on the aspect ratio@footnote 2@ and extent of overetching time. The suppression of this effect depends in a critical manner on achieving a balance between etching and deposition of passivating films.@footnote 3@ Deviations from such balance promote the appearance of grass or even excessive deposition of passivating films. We review the dependence of footing effect on etching conditions in a time multiplexed deep etcher (TMDE) and suggest specific operating conditions to preclude the appearance of notching even when overetching for as much as 85%. Additionally, we introduce the application of the footing effect in the microfabrication of free-standing structures, by demonstrating the micromachining of self-aligned, wafer-free electrostatic actuators for which etching, releasing, ashing and passivating (dielectric isolation) were done in the same piece of equipment. All processes needed to produce cantilevered structures are done in situ using VLSI compatible plasma chemistries only. The measured pull-in voltage for a 1000 µm cantilevered beam, of the order of 85 V, agrees with predicted values. The novel low-temperature, soft-mask scheme presented here, is compatible with other VLSI processes and can be easily integrated in the microfabrication of intelligent sensors and actuators. This robust new concept allows unparalleled fabrication simplicity while permitting the fabrication of sctructures and devices in an efficient and timely fashion. Electrostatic actuators with or without interdigitated fingers, valves, pumps and relays, to name but a few, are applications that immediately benefit with this technique. @FootnoteText@ @footnote 1@G. S. Hwang and K. P. Giapis, J. Vac. Sci. Technol., B 15 (70) 1997. @footnote 2@T. Nozawa, T. Kinoshita, T. Nishizuka, A. Naral, T. Inoue and A. Nakaue, Jpn. J. Appl. Phys., 34 (2107) 1995. @footnote 3@J. P. Chang, Ph. D. Thesis, Massachusetts Institute of Technology, 1997.

11:20am **MM+PS-MoM10 Test Structure Experiments and Modeling of Very Deep Dry Etching Processes for MEMS Applications**, ***S. Abdollahi-Alibeik***, *J.P. McVittie, K.C. Saraswat,* Stanford University

One successful approach for getting the desired high (~ 4µmm/min) etch rates for MEMS device fabrication is separating the etch and passivation steps in order to eliminate the interference in chemistry. The focus of this work is on the understanding and modeling of the very deep (>100µmm) trench etch process based on this approach. Experiments were done to investigate different aspects of both deposition and etch phases. C@sub 4@F@sub 8@ gas was used for the deposition phase. The deposited material is a CF@sub x@ polymer. It was observed that the deposition rate is highly dependent on the ion flux and ion energy received by the surface. This can be modeled as an increase in the effective sticking probability of the deposition species. While polymer deposition in an overhang test structure is not that conformal, the rate of passivation does not change when the trenches become very deep. The above model and the fact that the trench sidewalls receive little ion flux can explain this discrepancy. In addition, ion reflection also appears to be important since sidewall deposition shows a dependence on the opposite sidewall. For the etch phase SF@sub 6@ gas was used. Lag experiments show that the transport of the etchant species down the trenches depends on the deposition phase. The lag was higher for a larger ratio of etching to deposition time. The fact that ion bombardment of the CF@sub x@ polymer releases F atoms can be the reason for this change in lag behavior. Incorporation of the model into the SPEEDIE profile simulator will be shown.

11:40am **MM+PS-MoM11 Pattern Shape Effects and Artefacts in Deep Silicon Etching**, ***J. Kiihamaki***, *S. Franssila,* VTT Electronics, Finland

Deep silicon etching in inductively coupled plasma (ICP) reactor offers high etch rate, nearly vertical profile, and good selectivity against most common masking materials. Crystal orientation independent ICP etching can replace area consuming KOH wet etch in many micromechanical applications. We have etched various test structures with patterns of different sizes and shapes, using different etch chemistries and etch times. The widths of etched patterns range from submicron to over 100 µm, the etched depths were up to 500 µm. Long narrow features are etched faster than wide short features, indicating three dimensional nature of RIE-lag. Aspect ratio dependent etch rate is also present, further complicating design rule - process interactions. The difference in etch rate of a rectangular hole with respect to a trench of same width increases with aspect ratio and can be up to 20%. Typically narrow trenches have positive angled sidewalls and as trenches get wider the profile turns into retrograde, which implies serious limitations to device design. Positive or vertical profiles can be achieved if etch rate is lowered to 1-2 µm/min. Amount of etchable area also affects profile. Coalescence of closely spaced trenches into a larger feature (due to retrograde profile and/or undercutting) causes both etch rate and profile to change. Large area structures connected to narrow trenches assist the etching of the narrow trenches over considerable distances. To fully utilise the benefits of ICP etching, the design rules must be tailored for each application, because of various pattern shape effects.

Plasma Science and Technology Division
Room 318/319/320 - Session PS-MoM

Feature Evolution

Moderator: J.L. Cecchi, University of New Mexico

8:20am **PS-MoM1 The Independence of Feature Profile Evolution on Mask Charging During Chlorine Plasma Etching of Si (100)**, *K.H.A. Bogart, F.P. Klemens, V.M. Donnelly,* ***J.T.C. Lee,*** Bell Laboratories, Lucent Technologies

Non-ideal feature profiles including sidewall undercutting or bowing and microtrench formation at the feature bottom are often observed for crystalline (100) silicon (Si) with silicon dioxide (SiO@sub 2@) masks etched in pure chlorine (Cl@sub 2@) plasmas. Localized charging of the mask with respect to the underlying Si has been suggested as one possible cause for flawed profiles. Cl@sub 2@ plasma etching of Si (100) wafers (150 mm p-type, 4-200 @OMEGA@cm) with an insulating SiO@sub 2@ mask and patterned Si (100) wafers without a mask were compared directly to determine the effect of mask charging on the resulting feature profile. Etching was performed in a TCP plasma reactor (250 and 500 W rf source and 150 W rf bias power) at 2 and 10 mTorr Cl@sub 2@ . The pattern (nested and isolated lines and trenches) was transferred into the no-mask Si wafers by etching through a SiO@sub 2@ mask with a hydrogen bromide plasma, producing trenches with nearly vertical sidewalls and flat trench bottoms. The SiO@sub 2@ mask was removed in aqueous hydrofluoric acid, and the line and trench pattern was further propagated into the Si wafer by etching in Cl@sub 2@ plasmas under various conditions. In the latter case, the pattern through which etching proceeded was composed only of Si and was not insulating, but conductive. Therefore, localized charging of the patterned Si did not occur. Cross sectional scanning electron micrographs were used to compare feature profiles. In general, wafers etched with the insulating SiO@sub 2@ mask had line and trench profiles with bowed or tapered sidewalls and pronounced microtrenches. Wafers etched in the absence of the insulating SiO@sub 2@ mask showed nearly identical feature profiles. Therefore, localized charging of the insulating SiO@sub 2@2 mask is not a primary cause of sidewall bowing or microtrenching for Cl@sub 2@ plasma etching of Si under these conditions.

8:40am **PS-MoM2 Is Notch Formation Chemical or Physical?**, ***N. Hershkowitz,*** *A.K. Quick,* University of Wisconsin, Madison

There is debate in the etching community about what mechanisms are most important in the formation of notches in phosphorous-doped poly-Si lines during Cl@sub 2@ plasma etching. Some researchers claim that the notch is formed by ion deflection due to differential charging. Others claim that the ion deflection causes only the removal of SiCl@sub 2@ passivating films which then allows neutral etching of the notch. They claim that stress at the poly-Si/SiO@sub 2@ interface opens up the poly-Si lattice to enhance the neutral etch rate. The goal of this talk is to help clear up this controversy. An experiment was performed in which poly-Si line and space patterns were etched in the presence of an electron beam to reduce differential charging. An electron beam of the correct energy and current density was found to suppress notch formation, indicating that this phenomenon is charge related. Analysis of the notch shape for a floating and 13.56 MHz RF biased substrate (without the electron beam) showed a characteristically larger notch opening for the biased case due to the low-energy peak in the bimodal ion energy distribution function. This shape difference provided evidence that the notching phenomenon is mainly from ion deflection. In addition, scanning electron microscope images of the inside of the notch showed ion tracks that could not have been made by neutrals. These findings, along with the notch supression in the electron beam are proof that the dominant etching species are ions. This work is supported by National Science Foundation Grant #EEC-8721545.

9:00am **PS-MoM3 Feature Evolution Simulations of Silicon Trenches**, ***H.H. Hwang,*** *D. Bose,* Thermosciences Institute*; T.R. Govindan, M. Meyyappan,* NASA Ames Research Center

Understanding how an evolving microfeature is affected by process parameters, such as those that are controlled by knobs on the reactor panel, is of great interest. This is possible only if the feature level model is coupled to a reactor level model. We have developed a level set theory based profile evolution model to simulate the moving gas-solid interface between the semiconductor and plasma. This approach is an alternative to string algorithms which suffer from looping problems and are not easy to implement in three dimensions. Our model includes both the isotropic and anisotropic components of etching, and considers reemission of neutrals and ions inside the trenches. We have also developed a comprehensive reactor model which can provide the necessary input parameters for the level set simulation. The multidimensional reactor analysis code solves the complete set of Navier-Stokes equations for plasma transport, neutral species dynamics, gas flow, heat transfer, and Maxwell's equations for power deposition from an external source in a coupled manner to provide concentrations, fluxes, and energies of various species as a function of process parameters. We have validated the reactor model against available experimental data for N@sub 2@ plasmas (10 mTorr, 100 sccm) in a 300 mm etch ICP reactor. The current analysis shows that the model reproduces plasma properties, such as electron density, temperature, and their variations, with reasonable accuracy. We will present results from the feature profile simulation in pure chlorine plasmas in an ICP reactor at 1-10 mTorr and 20-100 sccm, based on the calculations generated from the reactor model. Comparisons to experimental data will also be presented. Support for Bose and Hwang provided by NASA contract NAS2-14031 to Eloret.

9:20am **PS-MoM4 An Integrated Multi-Scale Modeling Approach to Predicting Ionized PVD Step Coverages**, ***D.G. Coronell,*** *P.L.G. Ventzek, V. Arunachalam, C.-L. Liu,* Motorola*; D.E. Hanson, J.D. Kress, A.F. Voter,* Los Alamos National Laboratory

Ionized PVD has emerged as a promising technology for inlaid metallization over high aspect ratio features. However, the high cost of process and tool development and the need to forecast the extendibility of ionized PVD processes to smaller features and new materials represent major challenges. Computer-aided process development is an increasingly important means of addressing these challenges. Here we demonstrate how models describing phenomena at several length scales can be integrated to better understand, control, and predict the influence of process settings on ionized PVD step coverages. The relationship between the process variables and the flux of material to the wafer is determined using a detailed equipment scale plasma model.@footnote 1@ The ion flux information is subsequently funneled through a sheath model where the angular and energy distributions of the ions are computed for input to a feature scale model. This is a critical link in the integrated model as it enables a clear understanding of the relationship between equipment level settings and process performance at the feature scale level. An important component of the ionized PVD feature scale model is the description of the interaction of the energetic ions with the feature surface. The ion-surface interaction models were formulated from atomic scale molecular dynamics analyses where the angular and energy-dependent sticking probabilities, sputter yields, and directional characteristics of reflected and sputtered atoms were computed.@footnote 2@ The multi-scale model was applied to ionized Cu PVD where the effects of wafer bias, pressure, target power, and coil power on step coverage are illustrated for various feature geometries. As the feature sizes decrease, a judicial selection of process conditions is required in order to properly engineer the optimal mix of ionization and resputtering according to the model predictions. @FootnoteText@ @footnote 1@ See AVS '98 paper by Ventzek et al. @footnote 2@ See AVS '98 paper by Kress et al.

9:40am **PS-MoM5 Notch Formation by Stress Induced Etching of Polysilicon**, *J.P. Chang,* ***H. Sawin,*** Massachusetts Institute of Technology

We have demonstrated that notch formation during over-etching of polysilicon is in part caused by stress enhanced spontaneous etching and is not solely a result of feature charging. Mechanical stresses applied to patterned polysilicon samples were shown to be effective in enhancing or reducing the extent of notching formation. The tensile stress at the polysilicon-oxide interface enhances spontaneous etching of polysilicon by reactive neutrals and leads to the notch formation. Non-uniform stress fields are observed within the patterned lines and large localized stresses are induced at the interface, especially the corner adjacent to the substrate. Stress concentration at the polysilicon-oxide interface can enhance the surface kinetics of etching, thereby causing notching. Notching has been attributed to the electric-field-induced ion trajectory distortion and the subsequent etching of polysilicon by these ions near the polysilicon-oxide interface. The large local charging potential at the silicon dioxide surface is caused by the difference in the directionality of ions and electrons; i.e. the isotropically directed electrons charge the photoresist sidewalls negatively and the directional ions charge the underlying oxide positively during overetch. For submicron features, the potential necessary to deflect low energy ions (<45eV) to form notches is ~500V/μm (5V/100Å) on an oxide surface. However, the magnitude of this field is within a factor of two to the breakdown voltage for bulk oxide, ~1000V/μm. Such a large field is likely to cause leakage along the surface, reducing the field and thereby preventing the deflection of ions to the extent needed to form

notches. Even through bulk oxide, leakage is significant for 100Å thick oxide above applied voltages of 5V.

10:00am **PS-MoM6 The Influence of Insulator Charging on Ion Scattering and Feature Evolution During Plasma Etching**, ***M.A. Vyvoda***, *D.B. Graves,* University of California, Berkeley

As aspect ratios of structures etched during semiconductor device fabrication increase, the flux of scattered ions from sidewall surfaces can become a significant component of the total ion flux to the feature bottom. Previous work@footnote 1@ has suggested that details of this scattering can strongly affect the ultimate shape of the feature bottom and therefore the success or failure of the etch process itself. However, relatively few studies describe a systematic investigation of the effects of insulator (e.g., hardmask) charging on ion scattering and feature profile evolution even though it is known that such charging can perturb ion trajectories and therefore affect ion scattering behavior.@footnote 2@ Using numerical simulations of electron and ion dynamics within trench structures in order to self-consistently calculate the local charging potential on insulating surfaces, combined with realistic ion scattering distributions from feature sidewalls,@footnote 3@ we show that charging of insulating materials during the etching of both semiconductors and insulators can have a large impact on the ion flux distribution along the feature bottom. Parameters varied in the simulation include mask angle, ion angular and energy distribution function, electron temperature, and trench aspect ratio. In general, under conditions of relatively low ion energy, narrow ion angular distribution function and near-vertical mask sidewalls, ion trajectories can be significantly perturbed by insulator charging, resulting in different ion flux distributions on the feature bottom. The coupling between the perturbation of ion trajectories incident upon feature sidewalls and the subsequent scattering characteristics of these ions is especially important. These results show that under certain combinations of independent variables, neglecting ion trajectory perturbation due to charging can lead to qualitative as well as quantitative errors in the prediction of local etch rates. @FootnoteText@ @footnote 1@ T.J. Dalton et al., J. Electrochem. Soc., 140(8), Pp. 2395 (1993); @footnote 2@ M. Schaepkens and G.S. Oehrlein, Appl. Phys. Lett., 72(11), pp.1293 (1998); @footnote 3@ C.F. Abrams and D.B. Graves, submitted to J. Vac. Sci. Technol. A (1998)

10:20am **PS-MoM7 Feature Profile Evolution during the High Density Plasma Etching of Patterned Polysilicon**, ***A.P. Mahorowala***, *H. Sawin,* Massachusetts Institute of Technology

The two-dimensional Monte Carlo profile evolution simulator developed was used to explain the origin of artifacts such as double faceting of photoresist masks and feature bottom trenching observed during the high-density plasma etching of polysilicon, and to study the effects of feature charging on profile evolution. A designed set of experiments was performed earlier on photoresist patterned polysilicon samples on a Lam TCP 9400SE etcher varying the top power, bottom power and Cl@sub 2@ gas flow rate. The catalog of SEM micrographs generated suggested strong dependencies of the artifacts mentioned above on feature aspect ratio, product formation rate and product residence time in the etching chamber. In particular, the surface composition at the top of the photoresist lines was found to govern the top facet angle; greater the deposition of silicon-based etching by-products, the less steep the facet. The lower facet angle was found to be controlled by the feature aspect ratio and the sticking probabilities and fluxes of the depositing materials. Feature bottom trenching was strongly linked to sidewall bowing. Trenching was found to begin when the passivating species were unable to prevent the sidewalls from bowing; the focussing effect of the curved sidewalls on the directional ions was determined to cause trenching. Finally, the realistic feature charging problem incorporating bulk conduction and surface leakage was solved to understand its role in profile evolution. For example, the high potentials developed near the feature bottom corners were found to reduce the energies of the ions striking the corners and correspondingly lower the etching rates.

10:40am **PS-MoM8 Modeling of Finite 3-Dimensional Features in High Density Plasma Etching@footnote 1@**, ***R.J. Hoekstra***, *M.J. Kushner,* University of Illinois, Urbana-Champaign

The development of 2-dimensional profile simulators for fabrication of microelectronics devices has significantly progressed in recent years enabling modeling of etch profile evolution under many different processing conditions. Submicron device development and increasing device density leads to more complex and innately 3-dimensional features which require improved dimensionality in profile simulators. Two issues of concern are: 1) To what degree can 2-d simulators can be applied to modeling 3-d structures? and 2) What systemmatic perturbations to 2-d profiles are cause by 3-d structures (such as finite length trenches)? In this paper, results for the Monte Carlo Feature Profile Model (MCFPM) will be used to investigate the these issues. There are 2-d and 3-d versions of the MCFPM which are identical with the exception of increased dimensionality. Comparisons are made of profiles predicted by the 2-d and 3-d MCFPM for finite length trenches and square vias for etching of poly-Si in an ICP reactor using Cl@sub 2@. The aspect ratio of the trench and the angular spread of the ion flux were varied. In the center of "long" trenches (e.g., 1 µm x 4 µm) profiles from the 2-d model are similar to those from the 3-d model except that the etch rate is lower due to increased shadowing of reactants. As the ends of the trenches are approached (that is, one is near "3-plane" corners) increased sidewall sloping and curvature is predicted from the 3-d models compared to the 2-d model. This necessitates a greater amount of over-etching to fully clear these features than predicted by 2-d models. The effects of angular spread and asymmetry of the ion flux, and redeposition of etch products were examined to determine their role in 3-d profile evolution. With redeposition, we found that narrow ion angular distributions were more sensitive to being near 3-plane corners, resulting in more variation in transverse etch profiles along the trench. @FootnoteText@ @footnote 1@Work supported by SRC and NSF.

11:00am **PS-MoM9 Charging Effects in Profile Evolution during Etching of Silicon in High-Density Plasmas**, ***G.S. Hwang***, *K.P. Giapis,* California Institute of Technology

Charging effects are particularly important when high-density plasmas interact with patterned semiconductor surfaces containing mixed conducting and insulating layers. We employ the Direct Simulation Monte Carlo method to investigate the influence of mask charging by the electron shading effect on profile evolution of polysilicon during etching in a Cl@sub 2@ plasma. We compare simulation results with and without charging as a function of ion temperature and mask thickness. We find that microtrenching and sidewall bowing are significantly affected by mask charging as a result of ion trajectory deflection by the local electric field between the mask sidewalls. The magnitude of the effect depends strongly on mask aspect ratio and shape. Differences in profile evolution during etching of nested and isolated lines could also be attributed to charging. The results reaffirm that feature-scale modeling can no longer exclude mask charging effects.

11:20am **PS-MoM10 Effect of Residual Chlorine (Cl) Atoms for Notching Formation in a High Density Plasma Reactor**, ***H.C. Lee***, *Y.-B. Kim, S. Beckx, S. Vanhaelemeersch,* IMEC vzw, Belgium

Notching at the bottom corner of the etched polysilicon feature has been known as charging problem due to the electron shading effect,@footnote 1@ especially at the outermost line of the nested lines. Most of the experiments@footnote 2@ and simulations@footnote 3@ were conducted in a high density plasma reactor using Cl@sub 2@ chemistry. However, notching still occurs in the RIE reactors with symmetrical shape. We believe that notching can be formed due to the combination of plasma charging and preferable reaction between Si and Cl atoms. In this study, notching was investigated in terms of polymerization and chemical reaction between Si and Cl or Br atoms in a TCP 9400 high density plasma reactor. Mixed chemistry of HBr/Cl@sub 2@ and HBr/He-O@sub 2@ was used as a main etch step and over etch step respectively. From the TEM inspection of etched polysilicon profiles, the thickness of polymer which deposited on the sidewall decreases along down the sidewall. Much thicker polymer was detected at the top portion of the sidewall than the ones at the bottom. Thus, bottom sidewall exposed to the plasma without the protection layer against Cl atoms. Sidewall polymer was analyzed by angle resolved XPS in order to understand the polymer composition. TOA (Take of Angle) was varied from 15° to 90° which is normal to the horizontal gate oxide surface. Cl2p peaks were detected from the TOA35° to TOA65° which means most of Cl bonds are located at the sidewall of the feature. Si was also detected in the form of SiO@sub 2@ at the same TOA regime. At the TOA90°, however, intensity of Cl2p was very low, which explains that no Cl residues are on the etched gate oxide surface. It can be concluded that a lot of Cl atoms still remain on the sidewall even if it is not used during the over etch. In the meantime, Br3d peaks were detected whole range of TOA. With very low reaction probability of Br to Si, Br in the sidewall polymer also works as a protection layer. Consequently, notching has not been found in one step etching using HBr/He-O@sub 2@. Without the protection layer, 50nm thick SiO@sub 2@ was used as a mask material instead of photoresist, notching was increased dramatically. Residual Cl atoms play a major role in notching formation with combination of very thin polymer layer at the bottom corner of the features. @FootnoteText@

@footnote 1@K. Hashimoto: JJAP, 32, P6109, 1993. @footnote 2@T. Nozawa et al.: JJAP, Vol. 34, P2107, 1995. @footnote 3@G.S. Hwang and K.P. Giapis, Proceeding of P2ID, P63, 1997.

11:40am **PS-MoM11 A General Predictive Semi-Empirical Feature Profile Simulator***, **D.J. Cooperberg**, V. Vahedi,* Lam Research Corporation

A multiple process, semi-empirical, 2-dimensional, feature profile evolution simulator has been developed and is being used to conduct mechanistic studies of processes including oxide etch, silicon etch, PECVD, and IPVD. The feature surface is advanced with a shock-tracking algorithm@footnote 1@. The simulator employs a Monte Carlo based scheme for determining particle fluxes to the surface. Trajectories of ions, depositing and etching species are followed. Etching and depositing agents are modeled using a sticking coefficient model. A Langmuir site balance model is employed at the discretized feature surface to compute rates. For oxide etch, an algorithm for simultaneous etching and deposition has been implemented which allows for the modeling of a steady-state fluorocarbon film during etching@footnote 2@. Physical sputtering, ion-assisted etching and scattering of ions at the feature surface are modeled along with redeposition of sputtered material. Ion energy and angular distributions can be supplied to the profile simulator from self-consistent sheath models or simulations. Parameters such as stickling coefficients, sputter and etch yields which are associated with each material (i.e. photo-resist, oxide, polymer, metal) within a feature have been determined in part by experiment. Polymer deposition experiments have been performed to determine polymer sticking coefficients and study the role of ion-assisted deposition. Sputtering experiments have been performed to carefully measure angular and energy dependence of sputter yield on resist and oxide. Experimental results from IPVD have also been used to determine the yield and threshold for physical sputtering. Parameters not yet measured through experiment have been chosen with the use of a calibration routine which determines the values which lead to optimal agreement between simulation and digitized SEM data. The mechanistic and the semi-empirical calibration approaches have given our profile simulation tool a predictive capability. Feature characteristics such as taper, bow, necking, etchstop, facet angles, step-coverage and trenching are captured with appropriate process parameters. @FootnoteText@ @footnote 1@Hmamguchi S., "Mathematical methods for Thin Film Deposition Simulations", in "Modeling of Film Deposition for Microelectronic Applications," Thin Films, vol. 22, ed. by S. Rossnagel, (Academic Press Inc., San Diego, 1996), pp. 81-115 @footnote 2@ Rueger, N.R.; Beulens, J.J.; Schaepkens, M.; Doemling, M.F.; Mirza J.M.; Standaert, T.E.F.M.; and Oehrlein, G.S., Role of steady state fluorocarbon films in the etching of silicon dioxide using CHF@sub 3@ in an inductively coupled plasma reactor. Journal of Vacuum Science Technology A (Vacuum, Surfaces, and Films), July-Aug. 1997, vol.15, (no.4):1881-9.

Plasma Science and Technology Division
Room 314/315 - Session PS1-MoA

Environmental Issues and Emerging Technologies

Moderator: K.K. Gleason, Massachusetts Institute of Technology

2:00pm **PS1-MoA1 Scaling of PFC Abatement Using Plasma Burn-Boxes@footnote 1@***, **X. Xu**, M.J. Kushner,* University of Illinois, Urbana-Champaign

Perfluorinated compounds (PFCs), gases which have large global warming potentials, are widely used in plasma processing for etching and chamber cleaning. Due to underutilization of the feedstock gases or by-product generation, the effluent from plasma tools typically have large mole fractions of PFCs. The use of plasma "burn-boxes" located downstream of the plasma chamber is being considered as a remediation method for abating PFCs emissions. In the burn-box, typically located between the turbo- and roughing pumps, O@sub 2@ is injected into a high density plasma with the goal of converting PFCs into products such as CO, CO@sub 2@, and COF@sub 2@. Results from the 2-dimensional Hybrid Plasma Equipment Model (HPEM) have been used to investigate the scaling of plasma abatement of PFCs using burn-boxes with ICP reactors. The HPEM is used to model the etching chamber of the ICP reactor to determine the utilization of the feedstock gases and generation of by-products. The effluent from the etching chamber is then passed through the burn-box using O@sub 2@ injection and excited by a second inductively coupled source. Results will be discussed for Ar/CF@sub 4@/C@sub 2@F@sub 6@/O@sub 2@ mixtures. We found that reassociation of PFCs after dissociation in the burnbox, particularly problemmatic for CF@sub 4@, is an important by-product generation mechanism which can be controlled to some extent by controlling the gas temperature. The abatement of C@sub 2@F@sub 6@ is approximately 4 times more efficient that CF@sub 4@ due to both the cited reassociation and and larger dissociation cross sections for C@sub 2@F@sub 6@. Full oxidation of the PFCs is possible, though large mole fractions of O@sub 2@, typically on order of 50%, are required. The radius of the burn-box, skin depth of the inductively coupled field and residence time of gases in the burnbox must be optimally selected in order to minimize "pass-through" of the effluent which reduces the abatement efficiency. @FootnoteText@ @footnote 1@Work supported by NSF and SRC.

2:20pm **PS1-MoA2 Point-of-Use Plasma Abatement of PFCs in a High Density Inductively Coupled Plasma***, D.B. Graves, **E.J. Tonnis**,* University of California, Berkeley

A current major environmental concern in semiconductor manufacturing involves the use and emission of PFCs (perfluorinated compounds) and HFCs (hydrofluorinated compounds) during plasma etching of silicon dioxide and plasma-assisted chamber cleaning processes in dielectric film CVD systems.@footnote 1@ While significant progress has been made recently in reducing the emissions of PFCs and HFCs from CVD tools using alternate chemistries and process optimization, the stringent demands on oxide etch process recipes has limited emission reduction progress for etch. A promising alternate strategy for reducing or eliminating these emissions in etch processes is via point-of-use (POU) plasma abatement systems. In this approach, a high density plasma is ignited between the turbomolecular pump and the mechanical backing pumps downstream of a plasma process emitting HFCs and/or PFCs. A flow of O@sub 2@ is added upstream of the POU abatement plasma which dissociates the PFC/HFC and O@sub 2@ mixture causing the CF@sub x@ fragments to react with O atoms to form products that can be removed downstream through caustic water scrubbing processes. We present experimental results indicating that a high density, inductively coupled RF plasma can abate a variety of pure PFCs, including CF@sub 4@, C@sub 2@F@sub 6@, and CHF@sub 3@ in the presence of O@sub 2@ by between 90% and 99%. In addition, recent abatement experiments conducted on the effluent of an industrial high density oxide etcher indicate that these high levels of abatement can be realized even in the presence of complex mixtures of etch products found in actual tool exhausts. Issues that may limit POU plasma abatement implementation into an industrial environment such as process contamination, particulate formation, and transient control of the abatement plasma have also been examined. @FootnoteText@ @footnote 1@The National Technology Roadmap for Semiconductors, Semiconductor Industry Association, pp. 154-157, 1997.

2:40pm **PS1-MoA3 Plasma Etching Using PFC Replacement Chemicals***, T. Kure,* Hitachi Ltd., Japan*; T. Takaichi,* Showa Denko K.k., Japan*; **Y. Goto**,* Hitachi Ltd., Japan **INVITED**

PFC (Perfluorocompound) gases are widely used for plasma etching of thin film and for plasma cleaning of process chamber. However, unfortunately, PFCs have extremely long atmospheric lifetimes and absorb infrared radiation emitted by the earth that would otherwise be radiated into space. As a result, PFCs contribute to the greenhouse effect in the earth's atmosphere, thus helping to cause the phenomenon known as a global warming. To reduce the release of PFCs into the air, replacement chemicals and abatement devices for exhaust gases need to be developed. Recently, several kind s of abatement devices (combustion, plasma, thermal, and catalyst reaction) are being examined. In our research, we have focused on using iodofluorocarbons (IFCs) and unsaturated fluorocarbons (u-FCs) as replacement chemicals for PFCs. Since the binding energy of C-I bond and C=C bond are very weak compared with the C-F bond, the atmospheric lifetimes of IFCs and u-FCs are extremely short. Therefore, their impact on global warming should be small. For use in SiO@sub 2@ etching, we selected C@sub 2@F@sub 5@I and C@sub 3@F@sub 6@ because of its C/F ratio about 0.5, its boiling point less than room temperature, and nonflammability. We evaluated the SiO@sub 2@ and poly-Si etching rate in a microwave plasma with these gases comparing it with C@sub 4@ F@sub 8@ gas. We also evaluated XPS spectrum of deposited polymer on etched wafers. We found that both the etching performance and deposited material were similar among these gases. Therefore, we believe C@sub 2@F@sub 5@I and C@sub 3@F@sub 6@ can be used as replacement chemicals for PFCs in SiO@sub 2@ etching.

3:20pm **PS1-MoA5 Challenges in Plasma Etching and Patterning for Fabrication of New Systems and Devices***, **M. Engelhardt**,* Siemens AG, Germany **INVITED**

Among the most challenging tasks of plasma process technology today are, without doubt, plasma etching for fabrication of through-wafer interconnects in wafer stacks for vertical integration of chips (VIC) and plasma patterning of new materials used for electrodes and storage media in storage capacitors of Gbit scale DRAMs and FeRAMs. VIC realized by stacking and vertically interconnecting fully processed device wafers allows fabrication of both new systems with unique system qualities and systems with highly improved performance. 3D integration approaches are also driven by the interconnect crisis. Through wafer interconnects used for 3D chip integration require plasma etching of dielectrics, single cristal silicon, and interchip glue layers at aspect ratios exceeding 15 for vias through wafers thinned down to 15µm. Vertical profiles achieved with minimized RIE lags and high etch rates are the stringent requirements for all of these processes. Patterning of Pt electrodes is another challenging task. So far no volatile reaction products were obtained at usual process temperatures. Processes based on so-called reactive gases leading to a build-up of transient or removable sidewall films result in significant sidewall taper of the profiles and hence high CD gain whereas steep profile sidewalls have been obtained with processes based on inert gases with the tradeoff of build up of non-removable sidewall films. A new approach overcomes these tradeoffs by a combination of plasma patterning and CMP allowing fabrication of vertical Pt profiles with resist mask. The build-up of thin redepositions of Pt onto the sidewalls of the resist, obtained as a result of processing in pure Ar plasmas, is utilized to achieve a sidewall steepness of the patterned Pt film which is determined by the steepness of the pre-etch resist profile. After pattern transfer and resist stripping, the portion of the redepositions protruding above the fabricated storage node was completely removed by CMP.

4:00pm **PS1-MoA7 PECVD and Dry Etching on Large Glass Substrates for Flat Panel Displays***, **J.M. Perrin**,* Balzers Process Systems, France **INVITED**

Flat panel display manufacturing depends more and more on plasma processing. This is particularly the case in the fabrication of the thin film transistor (TFT) array for active matrix liquid crystal displays (AMLCD's). Besides PVD of metals or metallic compound films by magnetron sputtering, and PECVD of amorphous silicon (aSi) and silicon nitride or oxide, plasma dry etching is gradually taking over wet etching, still abundantly used in first and second generation fabrication lines. We will focus on process issues, reactor concepts, and architectures of processing tools for PECVD and plasma dry etching, both performed in RF-excited glow discharges. The evolution of process demand in PECVD goes towards i) a better control of film and interface quality to achieve thinner TFT's and improved aSi TFT mobilities, ii) the deposition of aSi films suitable for laser crystallization to produce polycrystalline Si TFT's, and iii) the deposition

silicon oxide instead of nitride as gate insulator. For dry etching the general trends are i) the development of dry-etching of metal source and drain contacts which is very critical in the back-channel etch TFT technology, ii) the reduction of the number of masks trend by etching multilayers of metals, and iii) etching of the ITO pixels. The increasing size of glass substrates to (up to 1 m2) imposes severe constraints on the design of reactors, to insure process uniformity, deposited film quality, and control of etch profiles. The most widely used concept still remains the classical capacitively-coupled RF discharge configuration. But the scaling up of such sources involve problems such as the uniformity of RF power distribution and gas feed on the electrodes. Moreoverreactive ion etching faces the problem that the RF discharge become more and more symmetric as the ratio of RF-powered electrode and grounded electrode areas tends towards unity. To overcome this problem of scaling-up, and provide control of the ion energy on the substrate, we have developed a new triode configuration (Piano reactor) involving a periodic structure of isolated bars with independent RF impedances to ground. Then comes the production issue related to the best way to achieve a large throughput. The debate is between the development of high rate plasma sources or processes with fast substrate handling in a cluster type configuration, or keeping moderate deposition and etch rate in stacks of reactor with parallel processing. Eventually reactor maintenance issues such as dry-cleaning after PECVD are critical.

4:40pm **PS1-MoA9 Use of a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) to Kill a Broad Spectrum of Microorganisms@footnote 1@***, **K. Kelly-Wintenberg**, A. Hodge, T.C. Montie, L. Deleanu, J.R. Roth, D. Sherman,* University of Tennessee*; P. Tsai, L. Wadsworth,* Textile and Nonwovens Development Center (TANDEC)

The medical, industrial, and food processing industries are constantly in search of new technologies to improve existing sterilization and pasteurization methodologies. Available techniques must deal with and overcome such problems as thermal sensisitivity and destruction by heat, formation of toxic byproducts, cost, and inefficiency in performance. We report the results of a newly invented plasma source, a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) that is capable of operating at atmospheric pressure in air and providing antimicrobial active species at room temperature. OAUGDP exposures have reduced log numbers of bacteria (E. coli, S. aureus, Deinococcus radiodurans, and Bacillus subtilis), bacterial endospores (Bacillus subtilis and Bacillus pumilus), and various yeast and bacterial viruses on a variety of surfaces. These surfaces included polypropylene, filter paper, paper strips, solid culture media, and glass. Experimental results showed at least a @>=@ 5 log@sub 10@ CFU reduction in bacteria within a range of 15-90 sec of exposure, whether the samples were exposed in conventional sterilization bags or directly exposed to the plasma. An exception to these very short exposure times were experiments with solid culture media where 5 min of plasma exposure was necessary to produce @>=@ 5 log@sub 10@ CFU reduction in bacterial counts. The effects of plasma treatment on bacterial cell structures were investigated by exposing cells to plasma for various durations and examining them by Transmission Electron Microscopy. These experiments showed cell lysis had occurred with the release of cellular contents. These data were consistent with spectrophotometer data in which the release of cellular constituents was measured as a change in absorption at 210nm and 260nm. With all microorganisms tested, a bi-phasic killing curve (logarithmic number of survivors versus time) was generated in plots of doseresponse data. Differences in susceptibilities of microorganisms observed on various surfaces suggested that the degree of lethality was dependent upon the time of diffusion of active species and the makeup of the microbial cellular surface. @FootnoteText@ @footnote 1@This work was supported in part by the Air Force under a STTR with Environmental Elements, Inc. of Baltimore, MD; and by the UTK Textiles and Nonwovens Development Center (TANDEC).

5:00pm **PS1-MoA10 High Pressure Plasmas as an Anti-Terrorist Technology***, **G.S. Selwyn**, H.W. Herrmann, I. Henins,* Los Alamos National Laboratory

Plasmas have long been used for production of short-lived, reactive chemical species needed for etching or deposition of thin films. Plasmas are also widely used for dry ashing or stripping of organic films, such as photoresist, from wafers. We have recently developed a novel, atmospheric pressure, non-thermal plasma source with chemical and electrical characteristics closely resembling traditional low-pressure plasma discharges. However, unlike conventional low pressure plasmas, this source produces a fast-flow stream of chemically-reactive, metastable species capable of selective surface oxidation. One emerging application for this new technology is the use of plasmas for decontamination of civilian and/or military targets attacked by chemical or biological warfare agents. We have demonstrated rapid and effective decontamination of surfaces exposed to either anthrax-surrogate spores or a chemical agent used as a surrogate for mustard gas. Anthrax is an air-borne, persistent and highly toxic spore capable of causing mass casualties if spread in an urban area by terrorist. The atmospheric pressure plasma jet (APPJ) has been shown to produce a 7-log decrease in active spores after a 90 second exposure to the reactive effluent stream. Mustard gas is a chemical agent causing severe skin blistering, mass injuries and incapacitation capable of lasting several months. It can be used to reduce the effectiveness of military force and to interfere with military logistics as well as to render urban areas uninhabitable for prolonged periods. The APPJ source has been shown to detoxify a mustard gas simulant by 5 orders of magnitude in just 30 seconds of effluent exposure. Development of this new technology provides a potential means of defeating terrorist attacks using these agents, both in the US and overseas. By providing a means to effectively counter chemical and/or biological attacks, it is hoped the use of these weapons of mass destruction will also be deterred.

Plasma Science and Technology Division
Room 318/319/320 - Session PS2-MoA

Diagnostics I

Moderator: M.L. Brake, University of Michigan

2:00pm **PS2-MoA1 Density Measurements of Cf@sub x@ in a GEC Reference Cell by Infrared Absorption***, **I.C. Abraham***[1]*, R.C. Woods,* University of Wisconsin, Madison*; G.A. Hebner,* Sandia National Laboratories

Tunable diode laser absorption measurements in the region around 1250 cm@super -1@ were used to determine line integrated CF, CF@sub 2@, and CF@sub 3@ densities in a GEC reference cell, modified for inductively coupled plasma operation. A quartz ring was also installed around the source region to stabilize and confine the plasma and to make the plasma chemistry more like that in industrial etch tools. The experimental layout involved a two pass arrangement, with the path including both the plasma and the space outside the glow region, in a plane just above the wafer surface. Two gas chemistries, C@sub 2@F@sub 6@ and CHF@sub 3@, and two wafer surfaces, bare silicon and blanket photoresist, were investigated. A range of pressure and power conditions, from 5 to 20 mTorr and from 100 to 300 W, respectively, was employed. The concentration of undissociated C@sub 2@F@sub 6@ in the C@sub 2@F@sub 6@ plasma was also measured. An intense spectrum of COF@sub 2@ can be detected in an O@sub 2@ cleaning plasma. The time evolution of CF, CF@sub 2@, and CF@sub 3@ in a C@sub 2@F@sub 6@ plasma was monitored, starting from a clean chamber and continuing for much longer than an etch cycle. The data should provide important benchmarks for models of oxide etching in inductively coupled plasma tools. This project was funded by SEMATECH under contract no. 38010430.

2:20pm **PS2-MoA2 Un-Collided Beam Mass Spectrometric Measurements in C@sub 2@F@sub 6@ and CHF@sub 3@ Dielectric Etch Discharges***, **J. RaviPrakash**,* The Pennsylvania State University, U.S.A*; R.C. McGrath,* The Pennsylvania State University*; G.A. Hebner,* Sandia National Laboratories

Relative concentrations of reactive ions, neutral radicals and etch/resist products in dielectric etch chemistries have been measured using an uncollided beam mass spectrometer (Hiden EQP). Measurements were made in C@sub 2@F@sub 6@ and CHF@sub 3@ discharges produced in an inductively coupled research reactor operating with power densities, pressures, gas compositions and wafer materials typical of those found in etch processing tools. For C@sub 2@F@sub 6@ discharges we find that CF@sub 3@@super +@ is consistently the dominant fluorocarbon ion present, in agreement with published cross sections for dissociative ionization. Significant concentrations of CF@super +@, CF@sub 2@@super +@, and C@sub 2@F@sub 5@@super +@ are also observed. We will report on differences observed between our measurements of fractional yields for these reaction products and those expected from published dissociative ionization cross sections. Notable changes have been observed in concentrations of C@sub x@F@sub y@ species and of SiF@sub x@ etch products in the presence of photoresist. In CHF@sub 3@ discharges the dominant ion species are CF@sub 3@@super +@ and CHF@sub 2@@super +@. Smaller concentrations of CF@sub 2@@super +@,

[1] **PSTD Coburn-Winters Student Award Finalist**

CF@super +@ and HF@super +@ are also observed. For each of the etch chemistries investigated, variation of species concentrations with changing power (100-400 W) and pressure (5-40 mTorr) were measured. We will report on discharge conditions which produce the maximum reactive ion species production within the processing reactor volume.

2:40pm **PS2-MoA3 Modeling High-Density Plasma Etching of Aluminum and Photoresist@footnote 1@***, P. Ho,* ***E. Meeks****, A. Ting, S.J. Choi,* Sandia National Laboratories

A plasma-etch mechanism has been developed to describe the high-density plasma etching of aluminum in BCl@sub 3@/Cl@sub 2@/Ar mixtures. Results of extensive validation comparisons with experimental data are shown for several different reactor models employing the aluminum-etch mechanism. Comparisons are made to diagnostic measurements of the gas-phase, including electron density, electron temperature, Cl@super -@ density, and relative radical densities, as well as to ion-flux and wafer-etch data from a commercial reactor. The reactor models employed include a well mixed reactor model and a 2-D axisymmetric plasma-flow model that can handle several, detailed surface-chemistry descriptions for different plasma-materials interfaces in the reactor. The gas-phase plasma chemistry mechanism includes dissociation, ionization, and excitation of etch products to accurately capture macroscopic loading effects. The gas-phase chemistry and aluminum-etch mechanisms provide very good quantitative agreement between the models and the wide collection of observations and measurements available in this study. Simulation results from the 2-D model predict well the measured radial uniformity for blanket-aluminum etching. In addition to the aluminum-etch mechanism, a simple description of photoresist etching is introduced, which reproduces most of the observed trends for blanket photoresist etching in the BCl@sub 3@/Cl@sub 2@/Ar plasmas. @FootnoteText@ @footnote 1@This work was supported by a Cooperative Research and Development Agreement between SEMATECH and Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000

3:00pm **PS2-MoA4 Studies of Ion Bombardment in Plasma Cleaning and Etching Gases***,* ***J.K. Olthoff****, Y. Wang,* National Institute of Standards and Technology

Ion-energy distributions and relative ion fluxes have been measured in a variety of plasma etching and cleaning gases, and their mixtures, at the grounded electrode of a high density inductively-coupled plasma (ICP) reactor. The gases studied include pure CF@sub 4@ and C@sub 2@F@sub 6@, along with the following mixtures: CF@sub 4@ + Ar, CF@sub 4@ + Ar + O@sub 2@, C@sub 2@F@sub 6@ + O@sub 2@, and SF@sub 6@ + Ar. All ions exhibited fairly simple ion-energy distributions that were indicative of the plasma potential. For pure CF@sub 4@, the two dominant ions observed were CF@sub 3@@super +@ and CF@super +@, but 3 other ions exhibited intensitites that were within a factor of 3 of the dominant ions. Similar behavior was observed in CF@sub 4@ + Ar mixtures with the addition of a significant flux of Ar@super +@ ions. For CF@sub 4@ + Ar + O@sub 2@ mixtures, 9 different ions exhibited fluxes whose magnitudes were within a factor of 2 of each other, thus indicating the complexity of the plasma-surface interactions in multi-component gases. In pure C@sub 2@F@sub 6@, CF@sub 3@@super +@ was the dominant ion, with only minor contributions observed from other ions. In mixtures of C@sub 2@F@sub 6@ and O@sub 2@, a host of other ions are formed, but the dominant ions are either CF@sub 3@@super +@ or O@sub 2@@super +@, depending upon the mixture. In SF@sub 6@ + Ar mixtures, all of the SF@sub x@@super +@ ions are observed, with the lower mass ions exhibiting larger intensities.

3:20pm **PS2-MoA5 Diode Laser Measurements of CF@sub x@ and CO Radicals in an Inductively Coupled GEC Reference Cell***, G.P. Deering,* ***W.L. Perry****, H.M. Anderson,* University of New Mexico

Diode laser absorption measurements have been made on CF, CF@sub 2@ and CO radicals in an inductively coupled GEC reference cell. The GEC reference cell was modified with a quartz confinement ring around the source region to stabilize the plasma. Optical emission and Langmuir probe studies indicated this modification resulted in fluorocarbon discharges with a plasma chemistry similar to that found in commercial etch tools. The experiments in this study focused on radical concentrations found in the reactor under typical high density plasma etching conditions. At 300 W source power, 100 W bias power and 10 mTorr C@sub 2@F@sub 6@ pressure in the GEC cell, etching proceeded at about 5000 A/min. A range of source power and bias power conditions, from 100 to 400 W and from 0 to 130 W, respectively, was employed. The time evolution of CF, CF@sub 2@ and CO in a C@sub 2@F@sub 6@ plasma was monitored during an approximate 2 minute etch cycle. Chamber cleanliness and bias was found to exert a strong influence on radical densities. The data is expected to provide an important database for models of oxide etching in inductively coupled plasma tools. This project was funded by SEMATECH.

3:40pm **PS2-MoA6 Cavity Ring Down Spectroscopy on an expanding Ar/C@sub 2@H@sub 2@ Plasma***, A.H.M. Smets, K.G.Y. Letourneur,* ***M.G.H. Boogaarts****, M.C.M. van de Sanden, D.C. Schram,* Eindhoven University of Technology, The Netherlands

In this contribution we present the first results obtained from a cavity ring down spectroscopy (CRDS) setup for the detection of low density species in a plasma reactor. In this reactor research is carried out on the use of an expanding plasma beam produced by a cascaded arc for the fast deposition of thin films. In the plasma beam acetylene is dissociated in several radicals which will react at the substrate to form hydrogenated amorphous carbon (a-C:H) films. At the moment the C@sub 2@H radical is considered to be responsible for the diamondlike quality of the a-C:H films. The aim of this project is to measure radical densities (C@sub 2@H, CH and H(n=2)) by using CRDS technique. CRDS is an absolute absorption technique based upon the measurement of the rate of absorption of the light pulse confined in an optical cavity. The absolute density of the n = 2 state of atomic hydrogen has been measured in an Ar/C@sub 2@H@sub 2@ expanding deposition plasma. From the measured H(n=2) densities it can be concluded that the C@sub 2@H radical is produced dominantly in an expanding Ar/C@sub2@H@sub2@ plasma. The results obtained by CRDS measurements on radicals will be used to develop a model for the growth of a-C:H films.

4:00pm **PS2-MoA7 VUV-Visible Emission Spectroscopy Investigation of Frequency Effects in Low Pressure Plasmas***,* ***A.C. Fozza****,* École Polytechnique, Canada*; M. Moisan,* Université de Montréal, Canada*; M.R. Wertheimer,* École Polytechnique, Canada

Low pressure (p@<=@10 Torr), high frequency (HF) plasmas have been used for many years in various processing steps in very-large scale integration (VLSI) manufacturing of integrated circuits, and are now increasingly used as an efficient method for surface modification of polymers. In order to optimize a particular plasma process, the operator can vary such "external" (operator-set) parameters as the HF power, pressure, feed gas composition, reactor geometry, excitation frequency, etc. In the present study, we focus on the effect of the excitation frequency, f, a parameter which has received relatively little attention in the literature over the years. The difficulties encountered in designing meaningful frequency - dependent experiments are the following: - varying f over a wide range requires that one change the reactor and/or the power-delivery system, which usually calls for a change of the plasma volume; - working at constant electron density, n@sub e@, or absorbed HF power density, P@sub a@, has frequently not been taken into consideration. These difficulties can be avoided by the use of surface wave discharges (SWD), which constitute the most thoroughly modeled type of HF plasmas. SWD plasma sources possess great flexibility: a very broad (continuous) range of excitation frequencies, wide ranges of operating pressures and plasma densities, and high coupling efficiency. In earlier experiments in these laboratories, we have examined f-dependence of plasma deposition and etching experiments.@footnote 1@ The present experiments have been designed to investigate f-dependence more "directly", by studying optical emission from pure gases or their mixtures, as recently reported for the case of 2.45 GHz excitation.@footnote 2@ The vacuum ultraviolet (VUV) to visible emission from SWD plasmas in pure hydrogen or 0.07 H@sub 2@/0.93 Ar mixture have been investigated over a broad range of excitation frequency (50@<=@ f @<=@ 200 MHz) using a spectrophotometer with a known (calibrated) transfer function. As in earlier experiments,@footnote 1@ we have been able to interpret the f-dependence of emission intensity (atomic lines and molecular bands) in terms of changes of the electron energy distribution function. @FootnoteText@ @Footnote 1@ M. Moisan, C. Barbeau, R. Claude, C.M. Ferreira, J. Margot, J. Paraszczak, A.B. Sá, G. Sauvé, and M.R. Wertheimer, J. Vac. Sci. Technol. B9, 8 (1991). @Footnote 2@ A.C. Fozza, A. Kruse, A. Holländer, A. Ricard, and M.R. Wertheimer, J. Vac. Sci. Technol. A16, 72 (1998).

4:20pm **PS2-MoA8 Plasma Sheath Electric Field Strengths Above a Grooved Electrode in a Parallel-Plate Radio Frequency Discharge**, ***U. Czarnetzki,*** Universitaet GH Essen, Germany*; G.A. Hebner,* Sandia National Laboratories*; D. Luggenholscher, H.F. Dobele,* Universitaet GH Essen, Germany*; M.E. Riley,* Sandia National Laboratories

During plasma etching of microelectronic structures, the direction and energy of the ions that strike the surface has a major influence on the characteristics of the etch profile. In an ideal case, the sheath electric field vector will be perfectly perpendicular to the surface so that ions accelerated from the bulk plasma above the wafer will strike the wafer surface at normal incidence. In reality, the wafer surface is a multidimensional surface with several layers of subsurface dielectric that can significantly modify the electric field direction and ion trajectories. To examine the details of the spatial distribution of the electric field strength in the sheath region above an electrode with surface structure, and to provide data to validate recent advances in multidimensional sheath models, we have measured sheath electric fields above a structured electrode. The magnitude of the sheath electric field above a grooved electrode was measured using a novel, two color, laser induced fluorescence technique. Spatially resolved electric fields in the sheath region were determined by mapping the field induced Stark splitting of the n = 14 level in atomic hydrogen. Measured electric field values are in good agreement with calculated values. This work was performed at the University of Essen. GAH thanks the Deutsche Forschungsgemeinschaft for a travel grant in the frame of the SFB 191. GAH and MER were supported by the United States Department of Energy (DE-AC04-94AL85000). Expert technical support by Rainer Fuhrer is gratefully acknowledged.

4:40pm **PS2-MoA9 Ultrahigh Frequency vs. Inductively-Coupled Chlorine Plasmas: Comparisons of Cl and Cl@sub 2@ Concentrations and Electron Temperatures Measured by Trace Rare Gases Optical Emission Spectroscopy**, ***V.M. Donnelly,*** *M.V. Malyshev*,* Bell Laboratories, Lucent Technologies*; S. Samukawa,* NEC Corporation, Japan

Using trace rare gas optical emission spectroscopy, Cl and Cl @sub 2@ number densities (n@sub Cl@ and n@sub Cl2@) and electron temperatures (T@sub e@) were measured for two source configurations of high-density chlorine plasmas. In one configuration, the reactor was outfitted with a spoke antenna, operated at a resonant ultrahigh frequency (UHF) of 500 MHz. Alternatively, the same reactor was configured with a single loop, inductively coupled plasma (ICP) source operated at a radio frequency of 13.56 MHz. Optical emission from trace amounts (1% each) of rare gases added to the main Cl@sub 2@ feed gas were recorded as a function of power and pressure, during slow etching of the SiO@sub 2@-coated Si wafer. Modeling was used to derive T@sub e@ from these data. Additional emission from Cl@sub 2@ (at 305.0 nm) and Cl (numerous lines between 700 and 900 nm), normalized to the appropriate emission from the rare gases (i.e. actinometry) was used to obtain n@sub Cl@ and n@sub Cl2@. In the ICP, T@sub e@ decreased monotonically from 5.5 to 1.2 eV as a function of increasing pressure between 1 and 20 mTorr. Conversely, with the UHF configuration, T@sub e@ was 3.3 eV, independent of pressure between 1 and 7 mTorr, and then decreased to 1.7 eV as pressure was increased to 27 mTorr. At the same input power (1000W), both sources resulted in electron densities of 1 x 10@super 11@cm@super -3@ at 3.5 mTorr, yet the UHF plasma was much less dissociated (30%) than the ICP (70%). This is attributed to differences in the electron energy distributions in the two plasmas, especially at low pressure, caused by differences in energy transfer from the E-field to the electrons, through collisions with the gas. @FootnoteText@ *Also at Princeton University

5:00pm **PS2-MoA10 Spectroscopic Measurements in an Inductively Coupled RF Discharge in Hydrogen@footnote 1@**, ***M.L. Huebschman,*** *R.D. Bengtson, J.C. Wiley, J.G. Ekerdt,* University of Texas, Austin*; V. Bakshi,* International Sematech

Spatially resolved electron temperature profiles, T@sub e@(r,z), and plasma density profiles, n@sub e@(r, z) were measured with a multi-chord, multi-channel optical emission spectrometry in inductively coupled hydrogen plasmas over a range of RF power and pressure in a semiconductor growth and analysis chamber. The intensities from eighteen simultaneous chords viewing the plasma were measured for ten hydrogen Balmer lines. The calibrated intensities were Abel inverted to give local densities of the upperstate populations. Spatially resolved temperature profiles were obtained from the ratio of line intensities. Electron density profiles, n@sub e@(r,z) were determined from a collisional-radiative model@footnote 2@ using the electron temperature, pressure balance, and the populations of levels n = 3, 4, 5, and 6. Measurements were made with hydrogen pressures of 5 - 50 mTorr and with input powers from 50 - 200 W. Measured density and temperature profiles will be compared with fluid models. There are clear indications of capacitive coupling in the profiles. These experiments and models are motivated by the desire to develop physically accurate computational models of a simple chemical system -hydrogen on silicon- in a simple geometry which could be verified by measurements. @FootnoteText@ @footnote 1@Research supported in part by the Texas Advanced Research Program. @footnote 2@L. C. Johnson and E. Hinnov, J. Quant. Spectrosc. Radiat. Transfer. Vol. 13, 333 (1973).

Plasma Science and Technology Division
Room Hall A - Session PS-MoP

Plasma Science and Technology Poster Session

PS-MoP1 Plasma-CVD with a Pulsed DC Glow-Discharge: A Time Resolved Experimental Investigation@footnote 1@, ***T.A. Beer***, *J. Laimer, H. Störi,* Technische Universität Wien, Austria

Pulsed direct-current (d.c.) glow discharges are commonly used in systems for plasma-assisted chemical vapour deposition (PACVD). In the present work we investigate the development of plasmas relevant for the production of TiN coatings. A videocamera with gateable image-intensifier is used to study the spatial and temporal evolution of the development of the plasma. Additionally, we use a single electrostatic probe to determine a time resolved charged particle distribution. Measurements are performed on a commercially available Plasma-CVD. Different steel-cylinders have been used as substrates. The typical shutter-speed used in our experiments is 100 ns. The pictures taken were used to generate MPEGmovies@footnote 3@ showing the plasma developement. Our investigations reveal large differences between plasmas with and without TiCl@sub 4@. In the absence of TiCl@sub 4@, the plasma ignites within the first 500 ns. In the presence of TiCl@sub 4@, the formation of the plasma along the substrates occurs with a certain delay, which has also been reported by Mogensen@footnote 2@. Our experiments show that the plasma ignites at the beginning of each pulse at one spot, where a positive column is observed, and spreads from there across the substrate surface. The pattern of the spatialtemporal evolution is quite complex and the evolution of the negative glow depends on various parameter, including geometry. The observed delays in the plasma formation are in the range of 10 us to 130 us. Detailed investigations of the time-dependent density of electrons and negative ions with our Langmuirprobe-setup are still in progress, first measurements show a high concentration of negative ions in the afterglow. @FootnoteText@ @footnote 1@ Supported by the Austrian Science Foundation FWF under Project No. P10794 @footnote 2@ K Mogensen, C Mathiasen, S Eskildsen, H Stöori, Surf. Coat. Technol.(in press) @footnote 3@ http://www.iap.tuwien.ac.at/www/plasma/mp_plasma/

PS-MoP2 Comparison of Feature Profile Evolution for Halogen Plasma Etching of Silicon (100), *K.H.A. Bogart,* ***F.P. Klemens***, Bell Laboratories, Lucent Technologies*; J. Lane,* Massachusetts Institute of Technology*; M.V. Malyshev,* Bell Laboratories, Lucent Technologies and Princeton Univ.*; V.M. Donnelly, A. Kornblit, J.T.C. Lee,* Bell Laboratories, Lucent Technologies

Feature profile evolution during halogen plasma etching of silicon-based materials is affected by several contributions to the etch mechanism. These aspects, including isotropic chemical etching, broad ion angle distributions, ion scattering within a feature, and redeposition of etching products, can cause deviations from anisotropic etching such as bowed or undercut sidewalls and mictrotrench formation in trench bottoms. Different halogen source gases produce various feature profiles and likely affect changes in the mechanistic components of silicon (Si) etching. Crystalline silicon (100) wafers (p-type, 150 mm) and poly-crystalline silicon (poly-Si) deposited onto silicon dioxide (SiO@sub 2@) were etched in a transformer coupled plasma reactor at two applied rf powers (250, 500 W, bias = 150 W) with Cl@sub 2@, HBr and HCl plasmas. Both Si (100) and poly-Si were patterned with nested and isolated lines and trenches using a SiO@sub 2@ mask. Scanning electron microscopy (SEM) was used to identify feature morphology and make comparisons between different halogen sources. Cross sectional SEM micrographs showed that HBr plasmas produced features with vertical sidewalls and little or no microtrenching. Deviations from anisotropically etched profiles (bowed sidewalls and deep microtrenches) were most severe for wafers etched in Cl@sub 2@ plasmas. Line and trench features for wafers etched in HCl plasmas evolved hybrid profiles; microtrenching and sidewall bowing occurred, but to a lesser degree than for Cl@sub 2@ plasmas. These data indicate that the presence of hydrogen or the type of halogen species in the plasma plays a significant role in feature profile evolution.

PS-MoP3 Plasma Damage in Metal Etch Processes Using an Oxide Hardmask, ***J.I. Colonell***, *N.A. Ciampa,* Bell Laboratories, Lucent Technologies, US*; M.V. Malyshev,* Princeton University*; V.M. Donnelly, J.T.C. Lee,* Bell Laboratories, Lucent Technologies*; C.P. Chang, K.P. Cheung, W.Y.C. Lai, C.T. Liu, C.S. Pai, H.M. Vaidya,* Bell Laboratories, Lucent Technologies, US

Plasma damage in metal etch remains a serious problem in ULSI fabrication, and is expected to become more severe as gate oxide thickness is scaled. One proposed solution is to use an oxide hardmask, rather than a photoresist mask, to pattern the metal. Metal to oxide etch selectivities of 8:1 are achievable, so the mask thickness can be reduced from 1 µm to 1500 Å, thus reducing the aspect ratio for 0.4 µm spaces from ~4 to ~2 or lower. This change should reduce damage by reducing electron shading and aspect ratio dependent etching. However, metal etch processes using hardmask generally require low pressure conditions (2 to 5 mTorr, compared to 10 to 20 mTorr for a typical photoresist process) which lead to higher plasma densities and electron temperatures. We have measured plasma damage due to metal etch in a commercial, high density, inductively coupled reactor on 0.25 µm technology CMOS capacitor and transistor testers, with oxide thicknesses from 50 Å down to 25 Å. The effect of source power (from 300 W to 600W) and process pressure (3 mTorr to 7 mTorr) on the damage will also be discussed.

PS-MoP4 2DINESE - Topography Simulation Software for Process Modeling and Optimization, ***I.V. Katardjiev***, Uppsala University, Sweden*; G. Carter,* Salford University, United Kingdom, U.K.*; S. Berg,* Uppsala University, Sweden

2DINESE@footnote 1@ is a powerful two-dimensional topography simulation program designed specifically for process simulation in IC R&D and manufacturing. It can simulate virtually all erosion and deposition processes currently employed in IC manufacturing - Reactive Ion Etching, Ion Beam Etching, Plasma etching, wet chemical etching, various PVD and CVD methods, multilevel metalization, to name a few. 2DINESE is built on a robust numerical implementation of the Theory of Surface Evolution, based on the generalized Huygens Principle of Wavefront propagation in anisotropic media. The basic points of this theory will be presented and its numerical implementation briefly discussed. Ample simulation examples will also be presented as well as a demonstration of the program will be given. @FootnoteText@ @footnote 1@ 2DINESE is freely available for academic use.

PS-MoP5 A Comparison of Oxide Damage in MOS Capacitors in Plasma Cleaning Applications, *X.M. Tang,* College of William and Mary*;* ***Q. Wang***, Keithley Instruments*; D.M. Manos,* College of William and Mary

This paper reports a study of a comparison of damage produced by three different sources for photoresist dry-cleaning and removal. The sources include a CW 1kW, 13.6 MHz TCP plasma source, a pulsed TCP source capable of operation at variable frequency and duty cycle, and a source creating a directed stream of energetic (1-10 eV) neutral oxygen atoms. By judicious choice of conditions among these three sources, it is possible to identify the relative contributions to gate oxide damage from ions, electrons, neutrals, and photons. Damage from contamination by deposition of wall materials or other impurities were also included in these studies. Test structures included MOS capacitors consisting of (Al/100 Angstoms of SiO2/Si). Source parameters were varied including pressure, RF power, gas composition, pulse length, and, in the case of neutral stream cleaning, reflected neutral energy and flux. Ion fluxes were estimated from measured plasma parameters and by calorimeter probe methods. Pre-exposure and post-exposure damage levels, under these variations of conditions, were measured using simulataneous high frequency and low frequency C-V and i-V techniques.Results are compared to damage assessments and to models which have previously been reported. Results showed less gate oxide damage in the neutral stream cleaning source. Residue removal and correlative surface damage from impurity effects are assessed by studies using XPS, STM, and Auger spectroscopy. Simulation models are used to correlate the process damage to the plasma discharge parameters.

PS-MoP6 Etching and Cleaning using a Pulsed ICP Plasma, ***D.M. Manos***, *X.M. Tang,* College of William and Mary

In this paper, we report studies of a pulsed ICP plasma using mixtures of argon, oxygen, water, hydrogen, and CF4 for removal of photoresist and cleaning and etching of SiO2. This paper reports measurements of the spatial and time-resolved electron temperature, plasma density, and measurements of the relative density of reactive species using optical emission spectrometry. Relative contributions of particle fluxes arising

from ion vs. neutral species are estimated from measurement using heat flux and momentum sensors. The rf antenna power was monitored with current and voltage probes for 2 kW operation into dummy loads and into etching plasmas. Etching and cleaning rates were measured as a function of rf power, pulse frequency, duty cycle, gas composition, using SEM, AFM and a quartz microbalance. The modulation frequency and duty cycle were varied to optimize cleaning and etching efficiency. Experimental results are compared to a globally averaged model published by Ashida et. al.@footnote 1@ and to particle-in-cell simulations performed in this work, using MAGIC.@footnote 2@ @FootnoteText@ @footnote 1@S. Ashida, et. al., J. Vac. Sci. Techol., A13, 2498, (1995) @footnote 2@B. Goplen, et. al., "Magic Users Manual", MRC/WDC-R-409, August 1997

PS-MoP7 Increase of Etch Resistance of Deep UV Photoresist by Implantation, ***K.K. Ong***, Nanyang Technological University, Singapore*; C.P. Soo,* National University of Singapore, Singapore*; M.H. Fan,* Chartered Semiconductor Manufacturing Ltd., Singapore*; A.J. Bourdillon,* National University of Singapore, Singapore*; M.H. Liang,* Nanyang Technological University, Singapore*; L.H. Chan,* Chartered Semiconductor Manufacturing Ltd, Singapore, Republic of Singapore

As device dimension shrinks, there is a need to use deep UV lithography to define sub-quarter micron features. However, most of the novel photoresists used in deep UV lithography generally face a problem: low etch resistance. In this study, implantation of various kinds of dopant into the resist layer was the approach to increase etch resistance. The first approach was that implantation of dopant into the resist formed a carbonized layer at the surface. The carbonized layer formed at the surface could be clearly observed on the cross SEM micrographs. This might increase the etch resistance by the assumption that the etch resistance is proportional to the C/H ratio of the resist (made by Wilson et al.). The etch rate of the treated resist was extracted from detailed experiment. Generally for both B and P implantation, the carbonized layer was thicker with increase implantation voltage. The thickness could reach to the range of around 0.5 μm. This enables a thinner resist (probably at 0.6-0.7 μm) used in the lithography, which enhance the resolution and the depth of focus. Secondly, implantation of Si into the resist might form the silylated resist which normally bears a higher etch resistance. Besides that, implantation of B or P into the oxide substrate increased the oxide etch rate greatly with respect to the above resist layer. The greater difference in the etch rate of the resist and oxide substrate gave a better etch selectivity.

PS-MoP8 An Integrated Surface Kinetics-Plasma Equipment Model for Etching and Deposition: Effects of Bias on Wall Reactions@footnote 1@, ***D. Zhang***, *M.J. Kushner,* University of Illinois, Urbana-Champaign

In high plasma density, low pressure etching tools, heavy particle reactions which occur at the walls are equally, if not more important, than heavy particle reactions which occur in the gas phase. To self consistently address these reactions, as well as to address reactions mechanisms occuring on the wafer, a Surface Kinetics Module (SKM) has been developed for the Hybrid Plasma Equipment Model (HPEM). The SKM is a surface site balance model which is employed at every mesh-point at the border between the plasma and surfaces. During each iteration of the HPEM, the fluxes and energies of species from the plasma to selected surfaces are used as input to a set of differential equations encompassing the surface reaction mechanism. The SKM then solves for the steady state values of surface coverages, processing rate (etching or deposition), and the species/fluxes leaving the the surface to the plasma. These values are then used to update the flux-in/flux-out boundary conditions which are used in the plasma portion of the HPEM. The SKM has been employed to investigate reaction mechanisms in Inductively Coupled Plasma (ICP) etching (oxide and poly-Si) systems with an rf biased substrate. With increasing rf biasing, the sheath voltage at surfaces other than the wafer also increase, thereby increasing the rate of sputtering of passivating species. These species return to the plasma, thereby increasing their flux to the wafer. The goal of the investigation is to determine whether the variation of these wall sputtering processes with rf bias amplitude is sufficient to significantly perturb the etching rate on the wafer. @FootnoteText@ @footnote 1@Work supported by SRC and NSF.

PS-MoP9 Investigations of Oxide Etching Using Validated Plasma Models, ***J.E. Johannes***, *T.J. Bartel, M. Gallis, E. Meeks,* Sandia National Laboratories

Future technology, 0.25 micron and below, will require continued use of high density plasma (HDP) etch reactors to perform dielectric etch of fine-line, high aspect ratio features using fluorocarbon gases. Applying plasma models to better understand and design this process is difficult due to the lack of chemical information. By coupling fundemental chemical data, diagnostic data, and reactor scale models a validated plasma mechanism and model can be developed for predictive HDP simulations. A three step process will be defined for developing predictive HDP models. This study will focus specifically on a C@sub 2@F@sub 6@ plasma for oxide etch, although the strategy can be applied to other lasma systems. First, a preliminary mechanism is developed using existing cross sections and beam studies from the literature. A sensitivity analysis is then used to reduce the number of reactions and species in a preliminary C@sub 2@F@sub 6@ mechanism to generate a 'manangable' chemistry set for 2-D/3-D simulations. Phase two of this process is mechanism and model validation; this step is required to have confidence in the model. O-D and 2-D simulations are compared to available C2F6 plasma data, from both experimental and commercial reactors, to suggest improvements in the chemistry models and to validate the plasma models. A wide range of data comparisons used for mechanism development and validation will be presented for this study including: spatially resolved langmuir probe data, laser induced fluoresence (LIF) data, diode laser absorption data, Hiden probe data and oxide etch rates. A suite of four different codes will be used: 1.) Aurora, a well stirred reactor model, 2.) MPRES, a 2-D finite element plasma model , 3.) Icarus, a 2-D Direct Simulation Monte Carlo (DSMC) plasma code and 4.) Pegasus, a 3-D version of Icarus. The final step in the process is to apply the validated mechanism to investigate commercial processes. The validated mechanism will be applied in the DSMC codes to study the effects of etch rate and uniformity as a function of gas injection and flow rate in a commercial HDP. In addition, Icarus/Pegasus simulations will be performed to investigate 300 mm scale-up issues.

PS-MoP10 Model for Etch Depth of Contact Hole, ***B. Abraham-Shrauner***, Washington University

A linear relation between the etch depth and the inverse diameter of a contact hole is derived approximately. The linear relation was found experimentally for contact holes etched in silicon dioxide and several models for it were computed.@super 1@ This linear relation can also be reexpressd as a function of time for which there is also data.@super 2@ The new feature is the application of Langmuir kinetics with synergistic etching of neutrals and the ions. The neutrals are modeled for molecular flow in a pipe with a sticking coefficient equal to one.@super 2@ This assumption is supported by a recent finding that the etching (nondepositive) neutrals are not adsorbed appreciably on top of the same neutrals on the passivated walls of contact holes etched in silicon dioxide.@super 3@ The ions are modeled simply by a vertical beam since the directed ion energy fluxes at the center of the contact hole fall off slowly with depth. The effect of the depositive neutrals on the etch depth relation is estimated. Etch rates for the neutrals and ions are computed from data.@super 1@ @FootnoteText@ @footnote 1@ 1. S. C. McNevin, M. Cerullo and J.T.C. Lee, Bull. Am. Phys. Soc. 42 1707 (1997). @footnote 2@ H. H@um u@bner and M. Engelhardt, J. Electrochem. Soc. 141, 2453 (1994). @footnote 3@ A. Misaka and K. Harafuji, IEEE Trans. Elect. Dev. 44, 751 (1997).

PS-MoP11 Oxide Etch Characteristics of Inductively Coupled Plasmas Using Multipole Magnets for the Fabrication of Optical Waveguides, ***K.J. An***, *D.H. Lee, G.B. Yoo,* SungKyunKwan University, Korea*; J.H. Joo,* Kunsan National University, Korea, South Korea*; G.Y. Yeom,* SungKyunKwan University, Korea

Dry etching of silicon oxide is one of the key steps not only in the silicon integrated circuit fabrication but also in other applications such as the fabrication of optical waveguides. In case of the fabrication of optical waveguides, dry etching characteristics of anisotropic etch profile, low sidewall roughness to reduce scattering loss, and high SiO@sub 2@ etch rates with high etch selectivities over mask materials easily to etch the films over 10μm thick are required In this study, glass etch characteristics of inductively coupled plasmas using multipole magnets were investigated. Various fluorocarbon gases and their combinations were used as etch gases. The10μm thick glass layer on silicon wafers used in this experiment was grown by plasma enhanced chemical vapor deposition. As the etch mask material, 3000Å thick Cr patterned using an Ar ion beam etching technique was used. To investigate the effects of multipole magnets on the characteristics of the plasmas and etch properties, ion density and F radical intensity were measured with and without the magnets along with etch rates, etch selectivities, and etch profiles. Also, we have analyzed the etched glass surface by x-ray photoelectron spectroscopy(XPS) to investigate the change of stoichiometry and binding states of the surface materials. When the glass was etched, the significant increase of etch rate, the increase of etch uniformity, and changes in the surface composition

were obtained with the magnets together with the increase of ion densities and radicals. Using CF@sub 4@, 1000watts of inductive power, 5mTorr of operation pressure, -100Volts of dc-self bias voltage, and with the magnets glass etch selectivity over Cr higher than 30 and glass etch rate over 4500Å/min with anisotropic etch profiles and smooth sidewalls of 10µm thick etched glass waveguides could be obtained.

PS-MoP12 Consequences of Photon Injection in an Inductively Coupled Plasma@footnote 1@, ***E.R. Keiter***, *M.J. Kushner,* University of Illinois, Urbana-Champaign

The plasma chemistry used for PECVD and etching are usually complex and consist of many different neutral and ionic species, only a subset of which may be desirable. Due to the nonselective excitation and dissociation typically obtained in plasmas, it can often often be difficult to simultaneously optimize all process variables. For example, a plasma with optimally high ion flux may have other plasma parameters that are detrimental to the process, such as a larger density of a polymerizing radical. By using an auxiliary source of excitation, such as a photon beam for photolysis or photoionization, it may be possible to simultaneously optimize multiple plasma parameters. In this paper we present results from a numerical study of an Inductively Coupled Plasma (ICP) system which includes an auxilliary photon source. The Hybrid Plasma Equipment Model (HPEM) has been modified to include a Monte Carlo Photon Beam (MCPB) module and is the simulation tool used in the study. Photons in the MCPB are represented as numerical particles, and photon absorption is described by using a variable particle weighting method. Photon reactions are specified in the same manner as other chemical processes. Source rates for charged and neutral species which result from photon absorption are generated by the MCPB and used by the fluid module of the HPEM. We will present the results from a parametric study of the effects of an external photon source on species densities and plasma parameters for a Cl@sub 2@ etching system and Ar/SiH@sub 4@ deposition system. @FootnoteText@ @footnote 1@Work supported by Applied Materials, SRC and NSF.

PS-MoP14 Low-Temperature Helicon Assisted Reactive Evaporation of Sn-doped and Ge-doped Silica Films for Planar Waveguide Photonics, ***K.W. Gaff***, *A. Durandet, R.W. Boswell,* The Australian National University, Australia

Photosensitive silica films are a key technology in the development of silica based integrated optic devices. While the photosensitivity of silica glass doped with a variety of elements has been investigated for fibres, the development of photosensitive films for planar waveguides is still nascent. Previous research has concentrated on germanium doped silica films, often hydrogenated, and fabricated primarily by flame hydrolysis or PECVD, although ion-implantation techniques are also being researched. Fibre preform fabrication and flame hydrolysis silica film deposition normally involve temperatures around 1000°C, while temperatures during PECVD fabrication of silica films are typically 300-400°C. In the present work, we employ a unique process - helicon assisted reactive evaporation (HARE) - which combines three-crucible, electron-beam evaporation with a helicon source to generate a high density reactive plasma for thin oxide film deposition. The process enables deposition of hydrogen free, multi-component doped silica films at relatively low temperatures, typically between 100-150°C. Using this process, we were able to deposit tin-doped silica films. We compare the optical properties of the tin-doped films with those of germanium-doped films deposited using the same process and with germanium-doped films fabricated by the higher temperature processes.

PS-MoP15 In-situ Cleaning of GaAs and Al@sub x@Ga@sub 1-x@As Surfaces and Production of Ohmic Contacts Using an Atomic Hydrogen Source Based on a Reflected Arc Discharge, ***V.A. Kagadei,*** Research Institute of Semiconductor Devices, Russia*; D.I. Proskurovsky,* Institute of High Current Electronics, Russia

The existence of a thin-metal-film - semiconductor interface containing no contaminant is a necessary condition for the formation of high-quality ohmic contacts. Chemical treatment of the surface of a semiconductor is insufficient to provide an interface free from oxide. This is most pronounced for semiconductors showing high rates of oxidation of the surface, e.g., for Al@sub x@Ga@sub 1-x@As. A technology for production of ohmic contacts with n-type GaAs and n-type and p-type Al@sub x@Ga@sub 1-x@As has been proposed, such that the surface cleaning in a flow of atomic hydrogen (AH) and the deposition of a metal film are accomplished in a unified vacuum cycle. A feature of this technology is that the processes are conducted in a vacuum deposition system with a residual pressure of 3 10@super -6@ Torr for GaAs and (3-7) 10@super -7@ Torr for AlxGa1-xAs. The AH flow was produced by a reflected-arc-discharge-based source with a hollow cathode and a self-heating element. In the course of cleaning, the hydrogen pressure was 10@super -4@ Torr. The specimen temperature and the treatment time were varied in the range as follows: T = 100 - 400 C and t = 0.5 - 90 min. AuGe/GaAs interfaces have been produced with the contaminant content being below the sensitivity threshold of the method of Auger electron spectroscopy (AES). With some technological procedures having been executed, an AuGe/Al@sub 0.6@Ga@sub 0.4@As interface has been produced with the oxygen content less than 1% and the contents of other impurities below the AES sensitivity threshold. A comparative examination has been carried out for ohmic contacts produced using the technology proposed and the conventional technology based on "wet" chemical cleaning. The contacts produced by the proposed technology show a better morphology of the surface and of the contact area edge, high adhesion, and a low contact resistant; the process of their production features good reproducibility. Performance data of devices made using the new technology are reported. The technology developed is promising for production of shallow-lying contacts with GaAs and contacts with AlxGa1-xAs having a high Al content.

Plasma Science and Technology Division
Room 314/315 - Session PS1-TuM

Pulsed Plasmas

Moderator: N. Hershkowitz, University of Wisconsin, Madison

8:20am **PS1-TuM1 Simulation of a Pulsed-Power Inductively Coupled Chlorine Plasma**, ***V. Midha***[1], *D.J. Economou,* University of Houston

Low pressure high density plasmas are widely used for the fabrication of sub-micron semiconductor devices. Recently, pulsed power operation has emerged as a promising technique for reducing charge induced damage and etch profile distortion (e.g., notching) associated with conventional continuous wave discharges. This paper reports results of a fluid simulation of a pulsed-power inductively-coupled chlorine plasma. The mass, energy, and full momentum equations for the charged species are solved simultaneously with the Poisson equation and the Helmholtz equation for the electromagnetic power deposition profiles. A p-version, least-squares finite-element formulation of the glow discharge equations was developed which is capable of capturing sharp fronts in the sheath region without numerical diffusion. Also, this method is unconditionally stable circumventing the extremely short dielectric relaxation time constant of the system. Simulation results show spontaneous separation of the plasma into an ion-ion core and an electron-ion periphery, depending on the negative ion to electron density ratio. These results are in agreement with a semi-analytic model of the system. The influence of the rf bias frequency on the sheath dynamics and the ion flux and energy to the driven electrode during the afterglow was also examined. Significant oscillations of the ion flux were observed when the ion transit time through the sheath was about equal to the period of the applied field. Finally, the transition to a fully developed ion-ion plasma state and the dynamics of this new kind of plasma were studied.

8:40am **PS1-TuM2 Fluorocarbon Film Composition and Reactor Effluent from Pulsed PECVD of Difluoromethane, 1,1,2,2-Tetrafluoroethane, and Hexafluoropropylene Oxide**, ***C.B. Labelle***[2], *K.K. Gleason,* Massachusetts Institute of Technology

Low dielectric constant (< 2.5) fluorocarbon thin films were deposited from three precursors with relatively low global warming potentials: difluoromethane (CH@sub 2@F@sub 2@), 1,1,2,2-tetrafluoroethane (C@sub 2@H@sub 2@F@sub 4@), and hexafluoropropylene oxide (HFPO, C@sub 3@F@sub 6@O). For each feed gas, reactor effluent and film composition were determined as a function of pulsed plasma excitation on and off timing cycles. Fourier Transform Infrared Spectroscopy (FTIR) confirms only partial decomposition of the feed gas occurs in pulsed PECVD, and only a relatively small number of additional gas-phase effluent species are produced in significant concentration. A minimum reaction set has been proposed for each precursor to account for the major effluent species. Most notable for CH@sub 2@F@sub 2@ and C@sub 2@H@sub 2@F@sub 4@ pulsed plasmas is the competition between CF@sub 2@-producing reactions and HF elimination reactions. HFPO pulsed plasmas, due their lack of H, do not have this competition, but the presence of oxygen in the precursor is significant. Support for these reaction sets is also found from a comparison of film composition. In each case, the CF@sub x@ distribution, as well as the presence or absence of hydrogen in the film, can be explained by the proposed reaction sets. Most notably, the role of the competition between CF@sub 2@-producing reactions and HF elimination reactions is reflected in the CF@sub 2@ vs. quaternary carbon concentrations as determined by carbon-1s x-ray photoelectron spectroscopy. Precursors with dominant CF@sub 2@-producing reactions lead to films with larger CF@sub 2@ concentrations, whereas precursors with dominant HF elimination reactions lead to films with larger quaternary carbon concentrations. In the case of the HFPO films, the high CF@sub 2@ fractions are easily explained by the dominant decomposition of HFPO into CF@sub 2@ and trifluoroacetyl fluoride (CFOCF@sub 3@). More significantly, however, the absence of significant oxygen in the films can be traced to the formation of several very stable oxygen species in the pulsed plasma which exit the reactor without being further broken apart and incorporated into the film. Finally, the global warming impact of the pulsed plasma effluents, and thus, of each film deposition process, has been determined.

9:00am **PS1-TuM3 Surface Composition and Reactivities of Fluorocarbon Radicals from Pulsed Fluorocarbon Plasmas**, *N.M. Mackie,* Colorado State University*; J. Bard,* Butler University*; N.E. Capps,* ***E.R. Fisher***, Colorado State University

Pulsed fluorocarbon plasmas are becoming an increasingly popular method to deposit materials with high fluorine content for a variety of thin film applications and to reduce the adverse charging effects during dry etching. Despite the enormous bod y of work on continuous wave (CW) fluorocarbon plasmas, the underlying deposition and etching mechanisms in pulsed and CW plasmas are still controversial. Pulsed hexafluoropropylene oxide (HFPO) plasmas have been postulated to deposit films from surface reactions of CF@sub 2@ radicals even though the sticking coefficient of CF@sub 2@ is known to be low. We have performed a critical comparison of fluorocarbon films deposited from variable duty cycle pulsed and equivalently powered CW HFPO plasmas. We have determined the duty cycle dependence of CF@sub 2@ reactivities and relative gas phase densities from CW and pulsed HFPO plasmas using our Imaging of Radicals Interacting with Surfaces (IRIS) method, which combines spatially resolved laser-induced fluore scence (LIF) with molecular beam techniques.. Preliminary results show that CF@sub 2@ radicals indeed have a low reactivity in a 5% pulsed HFPO plasma with R = -0.1 ± 0.07 and that there is some surface production of CF@sub 2@ during pulsed plasma processing. In addition, time resolved optical emision spectroscopy (OES) has been used to track excited state atoms and radicals throughout the pulse cycle. Insights into the deposition mechanism of HFPO pulsed and CW plasmas will be discussed.

9:20am **PS1-TuM4 Pitting-Free Gate Etching by Lowering Bias Frequency in Pulsed ECR Plasma with a Divergent Magnetic Field**, ***H. Morioka***, *A. Hasegawa, D. Matsunaga, N. Abe,* Fujitsu Ltd., Japan

In the fabrication of ULSI beyond quarter micron design rule, very high selectivity to gate oxide is one of the essential issues for gate electrode etch process such as poly-Si etching. The reason for this is not only that the gate oxide is getting thinner as the device generation changes, but also that the gate oxide along gate electrodes in a dense pattern region is easily pitted like spikes during overetch (microtrenching), even though the selectivity to the oxide is high enough in the open space. Therefore, excessively high selectivity is required to suppress the pitting in most cases. There are roughly two approaches to achieve high selectivity. one is lowering ion energy by decreasing bias power, and the other is changing chemistry. However, these approaches have disadvantages, that is, lowering ion energy often causes profile distortion such as notching, and the chemistry of high selectivity is sometimes followed by etching residue, strong proximity effect, and "particle" problem because this kind of chemistry tends to enhance polymer deposition on the wafer and chamber wall. Therefore, we have studied effects of bias frequency and pulsed plasma, to suppress the pitting in an alternative way. Our experiments were performed on an ECR plasma etch tool with a divergent magnetic field. Several bias frequencies between 13.56 MHz and 400 KHz with CW and pulsed ECR plasma sources were used to examine their effect to µ-loading of the selectivity and sub-trench depth of half-etch profile. In this experiment, by using pulsed plasma, having a cycle of 100 µs and 25% - 50% duty, and lower bias frequency than 2 MHz, we found that the selectivity µ-loading and the sub-trench depth were decreased, and consequently, we have achieved vertical etched profile without the pitting of the thin gate oxide (2.5 nm). These results imply that the lowering bias frequency (and pulsed plasma) has the efficiency to suppress topography dependent variation of selectivity and etched profile.

9:40am **PS1-TuM5 Pulse-Power Hollow Cathode**, *A. Belkind,* ***J. Cai***, Stevens Institute of Technology*; R. Scholl,* Advanced Energy Industries

An oxygen plasma generated by a linear multiorifice hollow cathode (LMHC) is used for oil removal from metal strips. To operate the source with a DC power the cathode is constructed from stainless steel. The source has a power limit that determined by cathode overheating and consequential appearance of arcs that destroy the cathode. Stainless steel replacement by aluminum would substantially improve cathode cooling and increase the power limit. Unfortunately DC discharge in oxygen with an aluminum cathode is accompanied with arcing. One way to avoid arcing in to use pulse-power. In this work, pulse-power hollow cathode discharge is investigated. Pulse durations and frequency influences on an oxygen plasma generated in various hollow cathodes are studied. Implementation of pulse-powered aluminum hollow cathode for oil removal is discussed.

[1] **PSTD Coburn-Winters Student Award Finalist**
[2] **PSTD Coburn-Winters Student Award Finalist**

10:00am **PS1-TuM6 Diagnostics of Pulsed Plasmas, and the Use of Pulsed Plasmas as a Diagnostic Tool**, ***M.V. Malyshev***, *V.M. Donnelly,* Bell Laboratories, Lucent Technologies

Pulsed plasma (PP) experiments were carried out in a transformer coupled plasma (TCP) reactor in argon and chlorine plasmas. Time resolved electron temperatures (T@sub e@), electron energy distribution functions (EEDF), electron densities (n@sub e@), positive ion densities (n@sub i@ @super +@), and negative ion densities ~(n@sub i@ @super +@ - n@sub e@) were measured with combinations of trace rare gases optical emission spectroscopy (TRG-OES), Langmuir probe, and microwave interferometry (MWI). These plasma parameters were studied as a function of pressure and power and compared with CW plasma operation. Time resolved number densities of metastable states of rare gases (1s@sub 3@ and 1s@sub 5@) were determined from a model that computes TRG-OES intensities. As the RF power is switched on at the beginning of the 100 us pulse period in a 10 mTorr Cl@sub 2@ plasma, n@sub e@ is near zero and starts increasing slowly, while T@sub e@ rises rapidly to 8 eV and falls to 4 eV in 5 us and to 1.9 eV in 20 us. We also designed a series of PP experiments to circumvent an impediment (the lack and inconsistency of published cross sections for electron impact excitation out of metastable states) in our TRG-OES model. Time resolved OES signals and n@sub e@ (from MWI) were recorded and compared. The rise of optical emission excited from the ground state (e.g. Ar 750.4 nm) coincides with the rise of n@sub e@ during the plasma-ON period, while the emission that comes mainly from excitation out of metastables (e.g. Xe 881.9 nm) increases more rapidly. Assuming the ground state cross sections are correct, we used this comparison to scale cross sections for excitation out of the metastables. Recent theoretical calculations agree with our pulsed-plasma-corrected cross sections.

10:20am **PS1-TuM7 Pulsed Plasma Processing with Helicons**, ***C. Charles***, Australian National University, Australia **INVITED**

High density, low pressure plasma sources utilizing modulated power have been attracting much attention recently. By modulating the power it is possible to further optimize and control the performance of processing plasmas by changing the pulse frequency and the duty ratio. Pulsing is also of interest for studies of basic plasma physics and pulsed argon discharges are useful benchmarks for a better understanding of the more complex mechanisms involved in pulsed plasma processing with electronegative discharges. Experimental and analytical analyses of helicon discharges in continuous and pulsed excitation using various gases (argon, oxygen) are used to present the main features of pulsed plasma processing. Three phases can be distinguished in a pulsed discharge, the breakdown phase, the steady-state phase and the post-discharge, which affect the processing in various ways as a result of temporal changes in the ion energy distribution function, plasma potential, plasma density and electron temperature. Details on the pulsed deposition of silicon dioxide using silane/oxygen mixtures are given to illustrate the effect of those temporal changes on the quality of the deposited films.

11:00am **PS1-TuM9 Very High Density Helicon Mode Operation in WOMBAT**, ***R.W. Boswell***, *A. Degeling,* Australian National University, Australia

A Helicon Wave mode which exhibits a peak downstream density of greater than 10@super 12@ cm@super -3@ in argon (so called the "blue mode" because of bright ArII emission along the axis) has been oberved. The experimental conditions are : argon gas pressure of 3 mtorr, dc magnetic field of 100g and rf power input of 2 to 3 kW at 13.56MHz into a source region of 18 cm radius and 50 cm length using a double half - turn antenna. The nominal plasma density is about 10@super 11@cm@super -3@ when tuned for the normal Helicon wave mode under these conditions, and the blue mode appears sporadically for intervals of about 2 ms every few seconds. By pulsing the rf power for a duration of a few milliseconds it was found that the blue mode could be tuned to and operated more consistently, however the duration of the mode never exceeded a few milliseconds until the power level was increased above 4kW (where the blue mode operated continuously). B-dot probe measurements indicate that the wave phase velocity while the blue mode operates is about 3x10@super 6@ m/s, which has been shown previously to be the optimum velocity for resonant wave heating of plasma electrons to increase the ionisation rate.The instability of the mode on time scales of a few milliseconds may be due to a neutral pressure decrease in the source caused by ion pumping while the blue mode is operating. Once the blue mode is quenched the ion pumping stops and the pressure increases in the source, allowing the blue mode to return in a few milliseconds.

11:20am **PS1-TuM10 An Overview of Ion-Ion Plasmas for Semiconductor Processing@footnote 1@**, ***L.J. Overzet***, University of Texas, Dallas; *D.J. Economou,* University of Houston; *J.L. Kleber, S.K. Kanakasabapathy,* University of Texas, Dallas; *B.A. Smith,* Texas Instruments Inc. **INVITED**

Negative ions form in almost all discharges used in semiconductor etching and deposition. In addition, the presence of negative ions can impact nearly every aspect of the discharge: from the discharge chemistry and the formation of particulates to the discharge structure and the transfer of energy from the source to electrons. The presence of negative ions forces the question: Can negative ions be used effectively in plasma processing? Recently, several groups have been investigating whether or not negative ions can be used to process semiconductors and the results thus far have been encouraging. We have found that time resolved measurements of pulsed discharges can provide information on how negative ions can be used for surface processing. Negative ions are ordinarily trapped inside the plasma volume, but, pulsed plasmas allow for efficient negative ion extraction during the afterglow period because the negative ion to electron concentration ratio (electronegativity) can increase dramatically. Plasmas with very large electronegativities are often called "ion-ion plasmas." Ion-ion plasmas have such small electron densities, that the sheaths one ordinarily expects to form no longer form in the same fashion and negative ions can more freely reach processing surfaces. This change in the sheath structure during the transition to an ion-ion plasma should be detectable and a proposed "plasma four point probe" for detecting this transition will be presented as well. Finally, high density plasmas can facilitate negative ion extraction because the high densities make the sheaths thin and the plasma source is sometimes positioned far from the processing wafer allowing the electron average energy to be smaller near the wafer. @FootnoteText@ @footnote 1@ This material is based upon work supported by the National Science Foundation under Grant Nos. ECS-9257383 and CTS-9713262 and by the State of Texas Advanced Research Program under Grant No. 009741-043.

Plasma Science and Technology Division
Room 318/319/320 - Session PS2-TuM

Oxide Etching

Moderator: M.D. Armacost, IBM Microelectronics

8:20am **PS2-TuM1 Very Uniform and High Aspect Ratio Anisotropy SiO@sub2@ Etching Process in Magnetic Neutral Loop Discharge Plasma**, ***W. Chen***, *T. Hayashi, M. Itoh, Y. Morikawa,* ULVAC Japan Ltd., Japan; *K. Sugita, H. Shindo,* Tokai University, Japan; *T. Uchida,* ULVAC Japan Ltd., Japan

Magnetic Neutral Loop Discharge (NLD) plasma@footnote 1@ is a new plasma source for dry etching process, and characterized by a well coupling of the input electric field to the electron motion near the Magnetic Neutral Loop (NL) region. Therefore a dense plasma can be produced and controlled spatially by changing the position of the NL.@footnote 2@] As an evidence, uniform SiO@sub 2@ etching was successfully carried out in several kind of gases and/or those mixture by setting the suitable NL positions.@footnote 3@ Three topics are reported here, which are very uniform etching process by temporal and spatial NL control, high aspect ratio etching for nano-scale pattern in a CHF@sub 2@@super +@ rich plasma and effect of a simple parallel antenna structure for NLD plasma production. In the uniformity control, the deviation of SiO@sub 2@ etch rate was obtained within 3.0% (3 @sigma@) on 200mm diameter wafer, by changing the radius of NL temporally during the etching where the magnetic coil current was varied sinusoidally from a constant value with the repetition frequency of 0.1Hz. Meanwhile the etched profiles of the 0.4 micrometer hole pattern with about 2 micrometer in depth were almost vertical (about 89-90 degrees) at the wafer center and edge. In nano-scale pattern etching process, we found that CHF2+ ions played an important role in a very high aspect ratio profile etching. In a CHF@sub 2@@super +@ ion rich plasma ZEP photo-resist patterned 20nm space was successfully etched with 800nm in depth at the pressure of about 0.3Pa, where CH@sub 2@F@sub 2@, C@sub 4@F@sub 8@, O@sub 2@ gases were used. For plasma production, we proposed a parallel turn antenna, which is characterized in low inductance and larger volume plasma heating in comparison with a conventional single turn antenna. Therefore a high density, low electron temperature plasma with a large diameter of about 0.5m can be produced by 13.56MHz as well as 27MHz power supplies. @FootnoteText@ @Footnote 1@T. Uchida, Jpn. J. Appl. Phys., 33 (1994) L43 @Footnote 2@T. Uchida, AVS 44th National Meeting (1997) ID#98,

Conf. Paper #PS1-TuM1 @Footnote 3@W. Chen, M. Itoh, T. Hayashi and T. Uchida, ibid ID#207, Conf. Paper #PS2-WeM1

8:40am **PS2-TuM2 Microloading Effect in Ultra-Fine SiO@sub 2@ Hole/Trench Etching**, *Y. Chinzei, T. Kikuchi, M. Ozawa, M. Ogata,* ***Y. Feurprier****, T. Ichiki,* Toyo University, Japan*; H. Shindo,* Tokai University, Japan*; Y. Horiike,* Toyo University, Japan

The 10% trimethylsilane (TMS) added CF@sub 3@-O-CHF-CF@sub 3@ (HFE227)@footnote 1@ and CF@sub 3@-CO-CF@sub 3@ gas chemistries were found to provide high aspect ratio SiO@sub 2@ contact hole using Neutral Loop Discharge plasma. No microloading effect was found down to 0.15µm contact holes provided the bias voltage is high enough (500 V). A new XPS method was employed to analyse the SiO@sub 2@ bottom contact hole surface (aspect ratio about 2) in the course of etching. Prior to XPS analysis a very thin Al film is deposited to cover the resist layer. Then negatively biasing the substrate allowed the discrimination of the SiO@sub 2@ bottom contact hole surface from the top surface contribution. Playing an important role in the occurrence of microloading the bias voltage influence on the bottom SiO@sub 2@ surface composition was investigated for 0.45µm contact hole in the 200 V to 600 V range. The C1s distribution demonstrated C-rich polymer film as evidenced by the C-C component as the major contribution. The total amount of carbon was observed to decrease with increasing the bias voltage while that of F did not change significantly. This strongly suggested that increased bias voltages effectively decrease the polymer film thickness. Futhermore in order to clarify the limits of the HFE227-based chemistry a newly developped 75 keV EB lithography system was used to define line and space patterns of 40 nm to 250 nm using calixarene resist. The percentage of added TMS was slightly varied between 5% to 13%. High TMS addition to the fluorocarbon gas resulted in the occurrence of microloading. For example in the HFE227-based chemistry the microloading appeared for trench width below 50 nm and 110 nm for 10% and 13% TMS respectively. The space width measured at the top of the feature takes into account the increasing resist width due to the film deposition on the sidewalls. Finally no microloading was observed for the addition of 5% TMS then allowing the fabrication of 30 nm trenches. The fine effects of the TMS addition are not yet fully understood due to the complicated plasma and surface reactions involved. EB patterned fine hole array were also fabricated to further evaluate the microloading limits of this fluorocarbon gas chemistry. @FootnoteText@ @footnote 1@Y. Chinzei, M. Ogata, J. Takekawa, N. Hirashita, T. Hayashi, H.Shindo, T. Ichiki and Y. Horiike, PS-WeA10 AVS44th.

9:00am **PS2-TuM3 Selective Oxide Etching in a High-Density Plasma Reactor: Gas Phase Chemistry**, ***J.L. Cecchi****, T.M. Bauer, A. Inoue, M.E. Littau, M.J. Sowa,* University of New Mexico **INVITED**

Achieving a stable, reproducible selective oxide etch process in high-density plasma reactors continues to prove problematic, owing in large part to the complex chemistry on the wafer surface. The process relies upon polymerizing hydrofluorocarbon (HFC) feedstocks that produce simultaneous deposition and etching, which must be balanced to provide selectivity while avoiding etch stop. The process is further complicated by a preponderance of reactions occurring on internal surfaces, the composition and temperature of which may change in time. Much of this complexity is revealed in the gas phase chemistry that accompanies the selective oxide etch process, and in this paper, we explore the relationship between the gas phase chemistry and the etching characteristics. We measure the concentration of fluorocarbon precursors, including CF@sub 3@, CF@sub 2@, and CF, with wavelength-modulated diode laser spectroscopy. Atomic species concentrations are measured by optical emission spectroscopy and ion current is measured with a Langmuir probe. These measurements have been made in inductively coupled plasma (ICP) reactors using a variety of HFC feedstocks over a pressure range of 5 to 60 mTorr, ICP powers of 300 to 2500 W, wafer bias of 0 to 400 W, residence times from 0.1 to 1 s, and with varying distance between the ICP coil and the wafer. By exercising the reactor over this large range of parameter space, we are able to vary the concentrations of most gas phase species by over two orders of magnitude. We have analyzed our data with models which relate the polymer growth rate, oxide etch rate, and resist etch rate to the gas phase species concentrations. From this we are able to infer the role of the gas phase precursors, as well as extract kinetic parameters for the processes.

9:40am **PS2-TuM5 Analysis of C@sub 4@F@sub 8@/Ar/O@sub 2@ Plasma for High-aspect Contact Hole Etching using Narrow-gap RIE**, ***T. Tatsumi****, H. Hayashi, S. Morishita, S. Noda, Y. Hikosaka, M. Okigawa, M. Inoue, M. Sekine,* Association of Super-Advanced Electronics Technologies (ASET), Japan **INVITED**

Plasma characteristics and radical species in a dual-frequency (27/0.8MHz) parallel plate system were measured using various in-situ measurement tools, such as infrared laser absorption spectroscopy (IRLAS), appearance mass spectroscopy (AMS), and optical emission spectroscopy (OES). In particular, the densities of key radical species, C@sub x@F@sub y@, CF@sub x@, F, C, SiF@sub x@ and O were analyzed in conjunction with SiO@sub 2@ etch performance. We found that the radical composition could be controlled by limiting the number of collisions with electrons and the interaction with the wall materials, besides the composition of the inlet gases. The number of collisions with electrons can be described as @tau@N@sub e@<@sigma@v>, where @tau@ is residence time, N@sub e@ is electron density, @sigma@ is collision cross section of dissociation, and v is electron velocity. <@sigma@v> means integrated value of @sigma@v multiplied by normalized electron energy distribution function.@footnote 1@ When @tau@N@sub e@<@sigma@v> was large, C@sub 4@F@sub 8@ was dissociated excessively and the relative density of F radical increased. Under long-residence-time conditions, large molecules, such as C@sub x@F@sub y@ and SiF@sub x@, were also observed that were released from the top electrode surface made of Si. The etch rate and the selectivities to photoresist and underlying Si were affected by not only the [F]/[CF@sub x@] (x=1,2,3) ratio but also these depositive species, i.e., the large molecules. It was possible to suppress both the excessive dissociation of C@sub 4@F@sub 8@ and the excessive deposition of the large species under the short-residence-time condition. We achieved a 0.09 µm@phi@ contact hole with an aspect ratio of 11, under low [F]/[CF@sub x@] ratio plasma conditions established by a short residence time (6 ms), and under an optimized radical/ion flux ratio controlled by the Ar diluted process. @FootnoteText@ This work was supported by NEDO. @footnote 1@T.Tatsumi et al., Jpn. J. Appl. Phys., 37 (1998); to be published.

10:20am **PS2-TuM7 Plasma Kinetics of Silicon Dioxide Etching with Fluorocarbon**, ***H. Chae****, H. Sawin,* Massachusetts Institute of Technology*; M.T. Mocella,* DuPont Fluoroproducts

Plasma kinetics of silicon dioxide etching was studied in various conditions: i) oxide cleaning after PECVD(plasma enhanced chemical vapor deposition) ii) oxide etching in an inductively coupled plasma. Chamber cleaning after PECVD of silicon dioxide is known to be one of the major emission sources of perfluorocompounds (PFCs) which have high global warming potentials and very long atmospheric lifetimes. Silicon dioxide etching mechanism in the cleaning condition was studied in this work with various kinds of fluorine containing compounds such as C@sub 2@F@sub 6@, CF@sub 3@CF@sub 2@OCF=CF@sub 2@ (PEVE), NF@sub 3@, F@sub 2@. Silicon dioxide was etched in high temperature of 400@degree@C in parallel plate plasma reactor after TEOS (tetraethyl-orthosilicate) oxide deposited by PECVD. The kinetic study using actinometry measurement of atomic F shows linear correlation between silicon dioxide etching rate and F atom concentration. Arrhenius plots show low activation energies about 0.05 eV below 100 @degree@C and about 0.16 eV above 200@degree@C. The activation energy measurement indicates that ion-enhanced etching is dominant mechanism below 100@degree@C and F atom spontaneous chemical etching is dominant above 200@degree@C. Silicon dioxide etching in high-density plasma can provide high etching rate and good directionality without device damage. However, there are a lot of concerns about RIE(reactive ion etching) lag, inverse RIE lag, etch stop and low photoresist selectivity. Profile evolution modeling can reveal the mechanism of the concerns mentioned above as well as other detail feature profiles like bowing, trenching and faceting. However, parameters for the profile modeling are not available. In this study an inductively couple plasma reactor was built with diagnostic capabilities of mass spectrometer and quartz crystal microbalance. Oxide etching and fluorocarbon deposition rate dependence on ion energy, ion-to-neutral flux ratio, ion impingement angle, and surface temperature were measured. At the same time, ion composition was measured with mass spectrometer.

10:40am **PS2-TuM8 Effect of Ion Bombarding Energies in Silicon Dioxide Etching**, ***Y. Hikosaka****, H. Hayashi, K. Kinoshita, S. Noda,* Association of Super-Advanced Electronics Technologies (ASET), Japan*; H. Tshuboi, M. Endo, N. Mizutani, Y. Nagata,* ULVAC Ltd., Japan*; M. Sekine,* ASET, Japan

Ion energy is one of the key parameters in the fabrication of high-aspect-ratio contact holes. Ions incident to the wafer have both high- and low-

energy components that depend on the bias frequency and the ion transit time across the rf sheath. However, the relationship between ion energies and etching characteristics such as rate, selectivity, profile and RIE-lag have not been well understood. Our goal is to clarify the role of high- and low-energy ions in SiO@sub 2@ etching. We used a planar-type NLD plasma source operating at 13.56 MHz. An rf-floating ion energy analyzer with a mass spectrometer was equipped inside the rf-biased electrode to measure IEDs (ion energy distributions) and ion fluxes at the rf-driven electrode. First, IED measurements were made for Ar/C@sub 4@F@sub 8@/O@sub 2@ plasma at rf biases of 2 and 13.56 MHz. The CF@sub 1@@super +@ ion is the dominant species for both bias frequencies. The ion energies of CF@sub 1@@super +@ were distributed from 89 to 715 eV at 2 MHz, wider than at 13.56 MHz. Next, we measured SiO@sub 2@ etch rates, self-bias voltages and IEDs as a function of bias rf power for both frequencies. We found that the etch rates were defined by the energy and flux of ions mainly at the higher peak region of the IED, whereas the each energy-splitting width of the IEDs and the self-bias voltage at 2 MHz were different from those at 13.56 MHz. Next, we estimated the energy dependence of the etch yield under actual etching condition, using the obtained IEDs and etch rates. We found that the etch yield of SiO@sub 2@ increased monotonically with increase in ion energy and tended to saturate at a value of 1.5 molecules/ion at energy levels exceeding 800 eV. This energy dependence of the etch yield led to a 65 % contribution of high-energy ions to the etch rate. @FootnoteText@ This work was supported by NEDO.

11:00am **PS2-TuM9 Studies of High Density Oxide Etch Mechanisms with a Physically-based Profile Simulator**, ***V. Vahedi,*** *D.J. Cooperberg, J.M. Cook, L. Marquez, E. Hudson, J. Winniczek,* Lam Research Corporation

Dielectric etching accounts for about forty-five percent of the etch steps in a semiconductor fabrication process, and with emerging device integration technologies this percentage will soon increase. In contrast to other etch processes, highly selective dielectric etching using high density fluorocarbon plasmas results in simultaneous etching and deposition. In order to implement dielectric etching successfully in a production environment, it is critical to understand how to balance the etching and deposition components. The required balance will be a strong function of the properties of the microstructures being produced as well as the aspect ratio of the features. While there are many proposed mechanisms to explain the dependence of this balance on aspect ratio, it is not clear which mechanisms are the dominant ones under a given set of process conditions. We are using our semi-empirical profile simulator to investigate the relative importance of various mechanisms leading to aspect ratio dependent etching (ARDE) in dielectric etching. Our dielectric etch model includes ion-enhanced etching, physical sputtering and polymer deposition as well as realistic ion energy distribution functions. We will present the results of our polymer deposition experiments which were performed to determine polymer sticking coefficients and study the role of ion-assisted deposition in sub 0.5µm features. We will also present results from sputtering experiments which were designed to measure carefully the angular and energy dependence of sputter yield of photoresist and oxide. The rest of the parameters were set using our calibration scheme which leads to optimal agreement between simulation and digitized SEM data. We will also present typical profiles under various process conditions.

11:20am **PS2-TuM10 The Challenge of Predictive Profile Simulators for Dielectric Etch**, *G.S. Hwang,* ***J. Kenney,*** *K.P. Giapis,* California Institute of Technology

Current ULSI technology requires extensive plasma etching of dielectric materials, a need that will further increase with the anticipated move to copper interconnects and low-k dielectrics. The increased importance of dielectric etch, when combined with tighter tolerances for profile control at larger aspect ratios, presents a unique opportunity for fundamental research to assist in the development of etch processes in a timely and cost-effective manner. To be sure, understanding plasma etching of dielectric materials poses a challenge, considerably taller than that of metal or polysilicon etch for two reasons: a) Etching of dielectrics proceeds by more complex surface chemistry, involving simultaneous deposition and etch processes, and b) Differential surface charging is significant. These differences can lead to etch rate dependencies and profile irregularities that are unique to dielectric etching. Direct Simulation Monte Carlo techniques are used to study dielectric etch in high density plasmas. The simulations include sheath theory, microstructure charging, surface currents, and etching by a simple sputtering model. We explicitly investigate the etch rate dependence as a function of etch depth on plasma parameters and dielectric quality (as judged by a surface discharge threshold). The results suggest that ion shadowing (aspect ratio dependent) and surface currents (absolute depth dependent) play a crucial role in dielectric etch. Based on the simulations, we develop an empirical relationship to capture the etch rate dependencies on etch time, ion temperature, ion energy, surface discharge threshold, aspect ratio, and etch depth. The relationship describes well published etch rate data and reported parameter dependencies for various oxide etch chemistries and can be used to predict the etch stop occurrence. Furthermore, profile evolution simulations are performed to investigate the rigin of two profile peculiarities in oxide etch: microtrenching and sidewall bowing. The results indicate that ion scattering is not the dominant mechanism by which these irregularities form. Rather, charging effects at the trench bottom and mask sidewalls appear to be mainly responsible as asserted by a comparison of predicted with experimental profiles.

11:40am **PS2-TuM11 Control of Profile in High Aspect Ratio Contact and Via Etch**, ***C.H. Bjorkman,*** *K. Doan, J. Wang, B. Pu, H. Shan,* Applied Materials, Inc.*; N. Kuo, P. Chang,* Applied Materials, Taiwan

The purpose of this study was to investigate which parameters control the profile in high aspect ratio (HAR) dielectric etch. Holes with aspect ratios in the range 6:1 - 10:1 were etched in a low-to-medium density MERIE etch chamber. A common observation among the fluorocarbon chemistries we investigated was the variation in profile angle from the top to the bottom of the hole. For example, the profile of a close to optimized single step chemistry starts off with a taper angle of 86-87°. After reaching an aspect ratio of approximately 3:1, the profile starts to straighten out. However, this trend is reversed as endpoint is approached. Typically, the taper angle at the bottom of the hole is approximately the same as what we observe at the top of the hole. This tapered bottom profile tends to decrease the CD (critical dimension) with a resulting increase in contact resistance. We divided the profiles into three components in order to quantitatively analyze our results: (1) any flaring and/or necking observed in top portion of the hole, (2) bowing or taper in the center portion and (3) excessive tapering and/or rounding of the bottom of the hole. We found that any initial tapering will remain and thus give rise to flaring at the top of hole. This can be prevented by minimizing polymer deposition on the sidewalls during the first third of the etch. We achieved this by making the chemistry leaner, raising the pressure and raising the wafer temperature. Controlling the profile during the second portion of the etch turns out to be a compromise between preventing bowing and maintaining a large bottom CD. The main parameter controlling this portion of the etch was determined to be the pressure. As for the last portion of the etch, the tendency to taper and thus reduce bottom CD was found to be controlled by the DC-bias. We obtained a straighter profile by decreasing both pressure and B-field and thus increasing the DC-bias.

Electronic Materials and Processing Division
Room 316 - Session EM+PS+SE-TuA

Plasma Processing of Compound Semiconductors
Moderator: C. Eddy, Boston University

2:00pm **EM+PS+SE-TuA1 Thermally Induced Improvements on SiN@sub x@:H/InP Devices**, ***E. Redondo***, *N. Blanco, I. Mártil, G. González Díaz,* Universidad Complutense de Madrid, Spain*; R. Peláez, S. Dueñas, H. Castán,* Universidad de Valladolid, Spain

The electron cyclotron resonance (ECR) plasma technique has been recently proved to be optimum as insulator deposition method in Al/SiN@sub x@:H/InP devices.@footnote 1@ In this communication we present a study of the influence of rapid thermal annealing (RTA) treatments on the interface characteristics of Al/SiN@sub x@:H/InP devices. The insulator was obtained by the ECR plasma method at 200°C-deposition temperature. The films were deposited in two steps: we deposited first a film with x=1.55 and then another with x=1.43. Total film thickness was 500Å in one set of samples and 200Å in other. RTAs were conducted in Ar atmosphere during 30s in a temperature range between 400 and 800°C. The electrical characteristics of the devices have been obtained by capacitance-voltage (C-V) and deep-level transient spectroscopy (DLTS) measurements. Those films annealed between 400 and 500°C/30s in Ar atmosphere give structures with the minimum interfacial trap density. The interface trap density behavior with the annealing temperature has been observed to show the same trend with both CV and DLTS measurements, reaching lower values in the latest ones. The minimum interfacial trap density value achieved with the best annealing is of 3x10@super 11@ cm@super -2@ eV@super -1@, obtained for 400°C/30s annealing on the thinnest structure (200Å). Besides, DLTS measurements show the presence of features in the spectrum that are characteristic of phosphorus vacancies, V@sub p@, and deep centers. The annealing at 400°C/30s reduces the V@sub p@ content. This suggests that the nitrogen from the insulator is filling these vacancies so InP surface is being passivated. @FootnoteText@ @footnote 1@ S.García, I.Mártil, G.González Díaz, E.Castán, S.Dueñas, M.Fernandez. J.Appl.Phys, 83 (1), 1998, pp 600-603.

2:20pm **EM+PS+SE-TuA2 Damage to III-V Devices During Electron Cyclotron Resonance Chemical Vapor Deposition**, ***F. Ren***, University of Florida, Gainesville*; J.W. Lee, D. Johnson, K. McKenzie,* Plasma-Therm, Inc.*; T. Maeda, C.R. Abernathy, Y-.B. Hahn, S.J. Pearton,* University of Florida, Gainesville*; R.J. Shul,* Sandia National Laboratories

GaAs-based metal semiconductor field effect transistors (MESFETs), heterojunction bipolar transistors (HBTs) and high electron mobility transistors (HEMTs) have been exposed to ECR SiH@sub 4@/N@sub 2@, SiH@sub 4@/N@sub 2@O and SiH@sub 4@/NH@sub 3@ discharges for deposition of SiN@sub x@ or SiO@sub 2@ passivating layers. The effect of source power, rf chuck power, pressure and plasma composition have been investigated. Effects due to both ion damage and hydrogenation of dopants are observed. For both HEMTs and MESFETs there are no conditions where substantial increases in channel sheet resistivity are not observed, due primarily to (Si-H)@super o@ complex formation. In HBTs the carbon-doped base layer is the most susceptible layer to hydrogenation. Ion damage in all three devices is minimized at low rf chuck power, moderate ECR source power and high deposition rates.

2:40pm **EM+PS+SE-TuA3 Anisotropic Etching of InP using CAIBE (Cl@sub 2@/Ar): Importance of the Sample Temperature Stability and the Reactive Gas Distribution**, ***B. Lamontagne***, *M. Gagnon, J. Stapledon, P. Chow-Chong, M. Davies,* National Research Council, Canada

Process development has been performed for the dry etching of InP using our Chemically Assisted Ion Beam Etching (CAIBE) system (Ionfab 300 from Oxford Inst.). We studied the etching mechanisms in order to obtain vertical, deep and smooth InP sidewalls. Such etching profiles are essential for optoelectronic discrete devices such as turning mirrors, reflector gratings, deeply etched waveguides, etc. The CAIBE system has a 15 cm diameter R-F driven ion source, the ion beam is usually composed of argon while chlorine is introduced through the gas ring located in front of the heated platen. The sample temperature - a critical parameter when etching InP with chlorine - has been calibrated and monitored using a non-contact sensor: a diffuse reflectance spectrometer (DRS 1000 Thermionics Northwest Inc.). It gives an accurate temperature measurement of the sample itself using the shifting effect of the temperature on the absorption edge position of semiconductors. This diagnostic tool allowed us to monitor the sample temperature increase under ion bombardment (CAIBE process) for various conditions; sample heating and mounting technique, ion beam current and energy. In some extreme process conditions the sample temperature has increased from 20° C to 300° C in less than one minute. Our results point out the need to use a stable process temperature in order to obtain vertical sidewalls. The influence of the reactive gas distribution has also been investigated, for example, by modifying the gas ring design. Etching conditions characterized by vertical (>89°) and long (up to 15 µm) sidewalls and SiO@sub 2@ mask selectivity of 30 were obtained.

3:00pm **EM+PS+SE-TuA4 Hydrogen in Compound Semiconductors**, ***M.D. McCluskey***, *N.M. Johnson,* Xerox Palo Alto Research Center **INVITED**

Hydrogen can be inadvertently introduced at any of several steps in the fabrication of optoelectronic devices. In particular, incorporation of hydrogen can occur during growth, wet chemical processing, or dry etching. The most common consequence of hydrogenation is the passivation of dopant impurities, which leads to a decrease in the electrical conductivity of the material. The most successfully applied experimental technique for directly determining the involvement of hydrogen has been infrared-absorption local vibrational mode (LVM) spectroscopy, which will be illustrated with representative examples. In GaN:Mg grown by metalorganic chemical vapor phase deposition, hydrogen passivates Mg acceptors during the growth. Through experimental and computational studies it has been determined that hydrogen incorporated during growth forms electrically inactive complexes with Mg, and that a furnace anneal dissociates these complexes to activate the acceptor dopant. LVM spectroscopy was essential in the identification of the Mg-H complex. The observed frequency of the hydrogen LVM verified the theoretical prediction that hydrogen attaches to a host nitrogen atom. Recently, large hydrostatic pressures have been applied to compound semiconductors to probe the vibrational properties of hydrogen-related complexes. In GaAs, the pressure dependent shifts of hydrogen stretch modes provide clues about the location of hydrogen in the complexes. In AlSb, pressure was utilized to resolve a mystery as to why the Se-D complex gives rise to one stretch mode peak while the Se-H stretch mode splits into three peaks. This anomalous splitting is explained in terms of a new resonant interaction between the stretch mode and combination modes involving a wag mode harmonic and extended lattice phonons.

3:40pm **EM+PS+SE-TuA6 The Interaction of Electrons with Hydrogenated GaN(0001)**, *V.J. Bellitto,* ***B.D. Thoms***, Georgia State University*; D.D. Koleske,* Naval Research Laboratory

Although Group III nitrides have recently been used to produce blue LEDs and laser diodes, many surface properties and processes have yet to be fully understood. One issue important to many applications of these materials is the effect of hydrogen during growth and processing. For example, hydrogen has been reported to significantly affect incorporation of dopants, Group III constituents, and contaminants. We have studied GaN(0001) using low energy electron diffraction (LEED), Auger electron spectroscopy (AES), energy loss spectroscopy (ELS), and high resolution electron energy loss spectroscopy (HREELS). The ELS spectrum of GaN is seen to be particularly sensitive to exposure to atomic hydrogen (produced by a tungsten filament heated to 2073 K). A new peak appears at a loss energy of approximately 12 eV after atomic-hydrogen exposure but is not seen after exposure to molecular hydrogen alone. However, this peak is strongly affected by low energy electron irradiation of the surface. Substantial reduction in the 12 eV peak intensity is observed following exposure to 1.8 microamps of 90 eV electrons for two minutes. After 10 minutes of electron impingement on the hydrogen-atom-exposed surface, ELS spectra appear identical to those taken with no hydrogen atom exposure. Heating to 690 K is also seen to remove the hydrogen-related peak from ELS spectra. Recently, Gillis et al. have shown that simultaneous exposure of GaN to hydrogen atoms and low energy electrons results in anisotropic etching. Implications of these data for both surface science and etching of GaN will be discussed.

4:00pm **EM+PS+SE-TuA7 III-V Surface Plasma Nitridation: A Challenge for III-Nitride Epigrowth**, *G. Bruno,* ***M. Losurdo***, *P. Capezzuto,* MITER-CNR, Italy*; E.A. Irene,* University of North Carolina, Chapel Hill

A challenge in the growth and processing of III-V nitrides is the control and optimization of the substrate/epilayer interface. It has been reported that high quality epilayers of GaN and related materials can be obtained by nitridation of the sapphire and GaAs substrates before the film growth. Substrate nitridation allows to accomodate the lattice mismatch between substrates and GaN epilayers and crucially affects the cristalline quality and

structure of both the buffer and epitaxial GaN layers. In this contribution, the focus is on the nitridation process of GaAs and GaP (100) substrates to form GaN layers and of (0001) sapphire surfaces to form thin AlN. In order to elucidate the chemistry and kinetics of these solid state anion exchange reactions, the nitridation of (100) InP is also investigated. Nitridations are performed in a remote radiofrequency plasma metalorganic chemical vapor deposition (MOCVD) apparatus by exposing surfaces to the downstream flow of N@sub 2@ and N@sub 2@-H@sub 2@ plasmas, taking the advantages of low process temperatures and minimal surface damage. In situ optical diagnostics such as optical emission spectroscopy (OES) and spectroscopic ellipsometry (SE) are used to fingerprint in real time the gas phase and surface modifications, respectively. Thus, the chemistry and kinetics of the plasma-surface interactions are described toghether with the surface/interface composition and morphology. AFM analysis has been used to measure the surface roughness and to validate the effectiveness of plasma nitridation with respect to the conventional thermal nitridation by NH@sub 3@. Transmission electron microscopy (TEM) is used to highlight the different structural aspects of the nitride layers obtained by N@sub 2@ and N@sub 2@-H@sub 2@ mixtures. Optimizing the surface temperature and the N@sub 2@/H@sub 2@ ratio the formation of an interfacial As-rich layer in the GaAs/GaN growth is minimized, the nitridation depth is increased up to 15nm and compact and chemically stable GaN layers are obtained.

4:20pm **EM+PS+SE-TuA8 III-Nitride Dry Etching - Comparison of Inductively Coupled Plasma Chemistries**, ***H. Cho***, *Y-.B. Hahn, D.C. Hays, C.R. Abernathy, S.M. Donovan, J.D. MacKenzie, S.J. Pearton,* University of Florida, Gainesville*; J. Han, R.J. Shul,* Sandia National Laboratories

A detailed comparison of etch rates, etch yields, surface morphology and sidewall anisotropy has been performed for GaN, InN and AlN etched in Inductively Coupled Plasma discharges of BCl@sub 3@, BI@sub 3@, BBr@sub 3@, ICl and IBr. Etch selectivities of 100:1 for InN over GaN and AlN are obtained in BI@sub 3@ due to the relatively high volatility of the InI@sub x@ products and the lower bond strength of InN. The selectivities are much lower in the other chemistries. The etched surfaces of the nitrides are smooth over a broad range of source and chuck powers, pressures and discharge compositions, and there is typically a slight deficiency of N@sub 2@ in the near-surface (@<=@ 100Å) region. The etch yields for all of the chemistries are relatively low (@<=@ 2), indicating that the high ion flux in the ICP tool is a critical factor in obtaining practical etch rates for the nitrides.

4:40pm **EM+PS+SE-TuA9 Photoenhanced RIE of III-V Nitrides in BCl@sub 3@/Cl@sub 2@/Ar/N@sub 2@ Plasmas**, ***A. Tempez***, *N. Medelci, N. Badi, I. Berichev, D. Starikov, A. Bensaoula,* University of Houston*; A. Chourasia,* Texas A&M University

Boron nitride (BN) and gallium nitride (GaN) are known as superior semiconductor materials for UV optoelectronic and high power, high temperature applications. As a consequence of their high molecular bond strength, these materials are extremely difficult to etch. In order to address the device processing issue, reactive ion etching (RIE) tests were performed on BN and GaN thin films. Our experiments show that optimum etching occurs using BCl@sub 3@/Cl@sub 2@/Ar chemistries for GaN and Cl@sub 2@/Ar for BN. In the case of GaN, the BCl@sub 3@/Cl@sub 2@/Ar mixture results in the highest reported RIE GaN etch rates.@footnote 1@ Auger and x-ray photoelectron spectroscopy analyses of the etched surfaces always show a depletion of the surface nitrogen atomic composition which increases with the dc bias (rf power). The impurity incorporation, C and Cl also shows the same trend. In order to improve the etch rates at lower powers, a photoenhanced RIE process was investigated. A BCl@sub 3@/Cl@sub 2@/Ar/N@sub 2@ plasma in combination with a xenon arc lamp was utilized. Preliminary results show a 33% increase in GaN etch rates for a -220 V dc bias (100 W rf power). The dependence of etch rates, surface composition and chemistry, and surface morphology on dc bias (rf power) and photo-irradiation flux will be presented. In addition, the energy and angle distribution of the reaction species from nitride materials exposed to well characterized reactive beams were investigated. The results will be compared to those from RIE and Photo-RIE data and a model for the possible surface etch reactions will be discussed. This work was supported by funds from a NASA cooperative agreement #NCC8-127 to SVEC, a Texas Advanced Research Program Grant # 1-1-27764, and a Texas Advanced Technology Program Grant # 1-1-32061. This material is also based upon work supported by the U.S. Civilian Research and Development foundation under Award No. REI-247. @FootnoteText@ @footnote 1@N. Medelci, A. Tempez, E. Kim, N. Badi, I. Berichev, D. Starikov and A. Bensaoula, 1998 MRS Spring Meeting (in print).

5:00pm **EM+PS+SE-TuA10 Characteristics of Cl@sub 2@ -based Inductively Coupled Plasmas during the GaN Etching**, ***H.S. Kim***, *J.W. Jang, Y.H. Lee, G.Y. Yeom,* Sungkyunkwan University, Korea*; J.W. Lee, T.I. Kim,* Samsung Advanced Institute of Technology, Korea

Planar inductively coupled Cl@sub 2@-based plasmas have been used to etch GaN and etch properties having smooth and nearly vertical etch profiles with the etch rates close to 850 nm/min could be obtained with Cl@sub 2@-rich gas combinations. To understand the effects of plasma conditions on the GaN etch properties, The quarupole mass spectrometry(QMS), optical emission spectroscopy(OES), and an electrostatic probe have been used. Especially, the quadrupole mass spectrometer system we used in the analysis of the plasmas was configured with ion optics, energy filter, and integral electron impact ion source for plasma diagnostics. Therefore, not only the radical densities but also positive and negative ion densities and their energy distributions were also measured. As process conditions used to study the effects of plasma characteristics on the GaN etch properties, Cl@sub 2@ was used as the main etch gas and Ar, BCl@sub 3@, and CH@sub 4@ were used as additive gases. Operational pressures were varied from 5mTorr to 30mTorr while other conditions such as inductive power, bias voltage, and substrate temperature were fixed at 600 watts, -120 volts, and 70 centigrade, respectively. The relative amounts of reactive ions (Cl@super +@, Cl@sub 2@@super +@, Cl@super -@, etc.), Ga-containing etch products(GaCl, GaCl@sub 2@, and GaCl@sub 3@ for Cl@sub 2@ plasma), and nitrogen-containing etch products (N, N@sub 2@, NH@sub 3@, etc.) were estimated by the plasma mass spectrometric measurements. The results showed that the enhancement of GaN etch rate was related to the increase of Cl radical and reactive ion such as Cl@super +@, Cl@sub 2@@super +@, etc. measured by the QMS and OES during the Cl@sub 2@-based inductively coupled plasma etching. Therefore, chemical reactions between Ga in GaN and Cl and Cl@sub 2@@super +@ from Cl@sub 2@, under the sufficient ion bombardments to break GaN bonds, appear to be important in the GaN etching. More detailed analysis of plasmas and their relation to GaN etching will be given in the presentation.

Plasma Science and Technology Division
Room 318/319/320 - Session PS+MS-TuA

ULSI Technology

Moderator: M. Liehr, IBM T.J. Watson Research Center

2:40pm **PS+MS-TuA3 Front End Integration for ULSI Technologies**, ***W.A. Mueller***, SIEMENS Microelectronics, DRAM Development Alliance, Germany **INVITED**

Key frontend integration challenges for sub 0.25 µm technologies will be discussed. For device isolation shallow trench isolation (STI) has emerged as the main road; the different approaches for STI fill and planarization will be evaluated. For the transistor integration shallow retrograde wells, sub 5 nm gate dielectrics, dual work function gates and shallow source/drain junctions are the key technologies. Logic and DRAM applications are posing different boundary conditions for integration, thus leading to different solutions for the device architecture. For high packing density memory arrays and cell based designs selfaligned contact- and local interconnect schemes has to be integrated in the frontend process flow. As a DRAM specific topic the integration challenges for trench- and stack capacitors will be addressed.

3:20pm **PS+MS-TuA5 Transient Diffusion Effects in Silicon Technology**, ***C.S. Rafferty***, Bell Laboratories, Lucent Technologies **INVITED**

In modern silicon technology, there is a steady trend to reduce the "thermal budget" of fabrication processes. The intent has been to reduce the thermal diffusion of dopants. However low temperatures have exposed significant non-equilibrium diffusion effects. The most striking of these, transient enhanced diffusion, causes many unexpected influences on devices. Transient diffusion (TED) is the enhanced diffusion rate of dopants due to point defects introduced during ion implantation. The enhancement can be as much as four decades above thermal diffusion rates. TED by its nature is cooperative in nature, where implanting one species can lead to enhanced diffusion of all the other species in the wafer, even those located some distance from the implantation window. The effects of such local and remote diffusion transients on transistors is manifold. In some cases, the transistors may fail completely to function as intended, in others, their properties may be degraded or shifted from their intended targets. This talk describes some of the experimentally observed impacts of transient

diffusion in technology. It is shown how a better understanding of the materials science involved can lead to better devices.

4:00pm **PS+MS-TuA7 Technology Requirements for Logic ICs**, ***M. Brillouët***, France Telecom, France **INVITED**

The logic ICs are targeting an higher packing density for increased performances and cost effective manufacturing. In the 'front-end' part of the process (i.e. the transistor and the lateral isolation), this higher integration is obtained - along with higher operating frequencies and reduced power consumption - in shrinking the feature sizes. As the materials stay basically the same (i.e. Si and SiO@sub 2@), this trend stresses strongly the photolithographic techniques : the etch process has to define structures at the atomic level ; selectivity, CD and profile are key parameters to control in these features with such an high aspect ratio. The density of the interconnections ('back-end' part of the process) can be improved by shrinking the feature sizes and by increasing the number of metal layers. Unfortunately, if one stays with the classical Al/SiO@sub 2@ system, while shrinking the metal pitch, the performance of the integrated circuit is degraded : there is thus a growing need to move to new materials (e.g. dual Damascene copper lines and insulators with a lower dielectric constant). Advanced developments will be required in the etching of these materials and, due to the introduction of the Damascene approach, the equipment set will be radically changed in a manufacturing line. The metallisation process impacts strongly the behaviour of the transistor : plasma induced damage during processing degrades the active devices and specific care need to be taken in order to minimize this detrimental effect. Finally, as the number of metal levels is increased, manufacturability is a major issue in the cost of the final product: improving the defectivity level of the interconnects is a key point, as more than half the process steps are now involved in the fabrication of the interconnection system.

4:40pm **PS+MS-TuA9 Advanced Deep-UV and 193 nm Optical Lithography: The Role of Resists, Reflectivity Control and Resolution Enhancement Technologies**, ***O. Nalamasu***, *R.A. Cirelli, G.P. Watson,* Bell Laboratories, Lucent Technologies **INVITED**

The fabrication of integrated circuits with optical lithography faces several challenges as the industry is moving from I-line to deep-UV and 193 nm lithographies. For the immediate future, the technical challenges in developing manufacturing processes with k values below 0.5 have been identified and are the subject of intense R&D activity across the world. The low k lithography solution requires fundamental understanding of, as well as innovations in optical and resist materials, reflectivity control and resolution enhancement (mask and optical) techniques. In this presentation, we will detail our research efforts in Resist materials, Reflectivity control and Resolution enhancement techology areas with special emphasis on 193 nm lithography and identify the issues and opportunities in extending the optical lithography for patterning sub-0.1 µm devices. We will also demonstrate 60 nm resolution with 193 nm lithography by combining research advances in single layer resist, dielectric anti-reflective layer/hard mask with a levenson phase-shifting mask.

Plasma Science and Technology Division
Room 318/319/320 - Session PS-WeM

Plasma Damage

Moderator: J. Werking, Sematech

8:20am **PS-WeM1 Gate Oxide Damage: Testing Approaches and Methodologies**, ***C.T. Gabriel,*** VLSI Technology, Inc. **INVITED**

Plasma processing of MOS devices has the potential to induce damaging current flow through thin gate oxides. Many studies have undertaken to measure this damage, using what at first appears to be a bewildering variety of measurement techniques. A natural question to ask is, which measurement technique is best? Can't the industry standardize on a particular technique? Actually, to study gate oxide damage, a variety of complementary techniques is needed. There are two broad families of gate oxide damage measurement techniques: those that characterize the charging source independent of the gate oxide, and those that characterize the effect of the damage by examining gate oxide degradation. To study the damaging potential of the plasma itself, measurement devices include EEPROM transistors, MNOS transistors, contact potential difference, and direct measurement techniques. To study the effect that plasma damage has on gate oxide, electrical parameters are measured appropriate for capacitors and transistors, which are typically connected to large, conductive "antennas" over thick field oxide. To select the proper measurement technique, one must first have a fundamental understanding of the damage mechanism. Charging during plasma processing arises from two main sources: plasma nonuniformity and electron shading. Plasma nonuniformity is relatively independent of the wafer, so a wide variety of techniques can be used to predict or detect damage resulting from it. However, electron shading is essentially an interaction with structures on the wafer, so damage detection is critically dependent on the measurement technique. The options for measuring gate oxide damage will be reviewed and compared, leading to a selection of "application-specific" damage measurement techniques.

9:00am **PS-WeM3 Evaluation of Charging Damage Test Structures for Ion Implantation Processes**, ***M.J. Goeckner,*** *S.B. Felch, J. Weeman, S. Mehta,* Varian Associates*; J.S. Reedholm,* Reedholm

Charging damage is a critical issue in both current and future ion implantation systems. In conventional ion implanters, plasma flood guns have been used successfully to reduce charging damage. However, the development of sub-0.18 µm devices will make control of wafer charging more important. In addition, sub-0.18 µm devices will require novel doping technologies such as ultra-low energy (ULE) ion implanters or plasma doping (PLAD). Throughput requirements for these new technologies, and other issues, might also make charging damage more prevalent. Because of these concerns, we are examining the efficacy of two charging test structures. They are Varian Research Center's (VRC) proprietary charging test structures@footnote 1@ and the test structures on CHARM-2 wafers.@footnote 2,3@ These test structures operate on two very different principles. The VRC test structures use static "antenna" MOS capacitors, while the CHARM-2 uses programmable EEPROM's. Each system has distinct limitations and advantages. For example, the CHARM-2 wafer can be used to measure the maximum induced surface voltage; however the result is influenced by the elapsed time between programming, exposure and data collection. In comparison, the VRC result is static, but the precise value of the induced surface voltage can not be measured. Both structures will be put through a series of tests on both PLAD and traditional implanters. Comparisons will be made of sensitivity, temporal and spatial variability, as well as any potential limitations or advantages each might have for examining charging in ULE and PLAD implantation environments. @FootnoteText@ @footnote 1@S.B. Felch and S. Mehta in "Materials and Process Characterization of Ion Implantation," Edited by M.I. Current and C. B. Yarling, (Ion Beam Press, Austin TX, 1997), pp 288-295. @footnote 2@W. Lukaszek in "Materials and Process Characterization of Ion Implantation," Edited by M.I. Current and C. B. Yarling, (Ion Beam Press, Austin TX, 1997), pp 296-317. @footnote 3@CHARM-2 is a registered trademark of WCM.

9:20am **PS-WeM4 SPORT Measured Electron Shading Effects and Comparison with Computer Simulation**, ***S.C. Siu,*** *R. Patrick, V. Vahedi,* Lam Research Corporation

Electron shading is recognized as a major mechanism for plasma processed induced damage in commercial plasma etch chambers. As the semiconductor industry moves to smaller feature sizes and thinner gate oxides, shading induced damage becomes a greater concern. The shading effect is known to be more severe with higher aspect ratio features and high density plasmas. This study uses SPORT wafers to measure plasma parameters and the shading effect in a commercial plasma etcher. The advantage of using a SPORT wafer is that the plasma measurements are at the wafer surface. The SPORT wafer was used as a planar floating asymmetric double probe. Ion and electron currents were collected and the electron energy distribution calculated. Measurements were also done with patterned pads of different aspect ratio features. Differences in the ion and electron current were clearly seen between a bare and shaded pad. A PIC simulation was used to predict shading effects. The simulation is able to account for charged resist structures that cause electron shading. Comparisons were made between the simulation and the experimental results.

9:40am **PS-WeM5 Suppression of Charging Damage Caused by Electron Shading Effect in Gate Etching Technology**, ***K. Yoshida,*** *K. Tokashiki, H. Miyamoto,* NEC Corporation, Japan

Recently, the charging damage caused by electron shading effect has become a serious problem in etching processes using high-density low-pressure plasma. This effect causes profile distortion and/or gate oxide degradation. It is expected that these problems would be enhanced in sub-quarter-micron device fabrication because of their high aspect ratios. We reported in American Vacuum Society 44th National Symposium(PS-MoM8) that the profile distortion was suppressed by applying the high pressure(@>=@20 mTorr) and low source power in HBr gas plasma to over-etching step for 0.18 µmm gate etch process. Furthermore we have studied the correlation between the profile distortion and the gate oxide degradation in order to suppress the charging damage successfully. The impact of gas chemistry (Cl@sub 2@ and HBr) and pressure on charging damage was evaluated in gate etching. Especially we focused on the just and over etch period because the charging damage takes place in this period. Thickness of gate film and that of gate oxide were 200 nm and 4.5 nm, respectively. An initial-electron-trapping-rate (IETR) method was applied to monitor the charging damage. We measured dV/dt slope under 40 mA/cm@super -2@ stress current with antenna ratios ranged from 50 to 66,700. At low pressure (2 mTorr) Cl@sub 2@ and HBr plasmas, dV/dt slope increased significantly as the antenna ratio were over 10,000. The dV/dt reached about 10 mV/sec, which means serious damage took place. However, as increasing in pressure, dV/dt slope or charging damage was effectively suppressed (dV/dt@<=@2 mV/sec at 20 mTorr). It was also found that HBr plasma more effectively suppressed the damage than Cl@sub 2@ plasma. Interestingly, these damage test results corresponded to the dependence of the profile distortion on gas chemistry and pressure. One of reasons for the different damage result between Cl@sub 2@ and HBr correlates with the different plasma characteristics between them. Electron temperature(T@sub e@) and density(N@sub e@) for Cl@sub 2@ plasma were higher than that of HBr plasma at the pressure ranged from 2 to 20 mTorr. T@sub e@ and N@sub e@ decreased with increasing pressure, 4.2 to 2.9 eV of T@sub e@ and 2.5E10 to 9.5E9 cm@super -3@ of Ne for Cl@sub 2@ plasma. In HBr plasma, T@sub e@ and N@sub e@ were lowered to 2.6 eV and 4E9 cm@super -3@ at 20 mTorr. In conclusion, the gate oxide degradation caused by electron shading effect correlates with the profile distortion. And the use of relatively high pressure(@>=@20 mTorr) HBr plasma in just and over etch period is useful to suppress the charging damage caused by electron shading effect.

10:00am **PS-WeM6 Modeling of Charging Damage during Dielectric Deposition in High-Density Plasmas**, *G.S. Hwang,* ***K.P. Giapis,*** California Institute of Technology

The mechanism of charging up of interconnect metal lines during interlevel dielectric (ILD) deposition in high-density plasmas is investigated by detailed and self-consistent Monte Carlo simulations of pattern-dependent charging.@footnote 1@ The results suggest that the initial conformality of the ILD film plays a crucial role in metal line charging up and the subsequent degradation to the buried gate oxide to which the metal line is connected. Line charging occurs when the top dielectric is thick enough to prevent tunneling currents while the sidewall dielectric thickness still allows tunneling currents to flow to the metal line; the differential charging of the sidewalls, which induces the latter currents, is caused by electron shading. The simulations include a treatment of charge dissipation along the surface of the dielectric;@footnote 2@ surface currents can significantly decrease the cumulative charging damage when facile at small surface potential gradients. Charging damage during plasma-assisted ILD deposition could become a problem more serious than that occurring

during plasma etching and is expected to pose additional requirements to low-k dielectrics currently sought to replace SiO@sub 2@. However, under the assumptions considered, a dramatic reduction in charging damage can be accomplished by depositing a more conformal ILD film around the metal line and/or by increasing the ability of the film surface to dissipate charge. @FootnoteText@ @footnote 1@ G. S. Hwang and K. P. Giapis, J. Appl. Phys., Vol. 84, to appear on July 1, 1998. @footnote 2@ G. S. Hwang and K. P. Giapis, Appl. Phys. Lett., Vol. 71, 458 (1997).

10:20am **PS-WeM7 Silicon Oxidation Employing Negative Ion under Transformer Coupled RF Bias**, ***H. Shindo***, *T. Fujii, T. Koromogawa,* Tokai University, Japan*; Y. Horiike,* Toyo University, Japan

Directional silicon oxidation technique is highly required in various ULSI processes. Especially for trench isolation of memory cell, the oxidation should be directional but with low damage. For this purpose, a new method of negative ion assisted silicon oxidation has been experimentally studied employing a microwave O@sub 2@ plasma. A feasibility of directional silicon oxidation by negative ion was examined. The plasma produced in a 6 inch stainless-steel chamber was employed and the downstream plasma was mainly concerned because the negative ion was highly populated. Ion mass and energy analysis showed that the dominant negative ion was O @super -@ and its density was more than one order higher than O @sub 2@@super -@. The oxide film quality produced was analyzed by XPS, FTIR and ellipsometer. The oxidation depth under the positive DC biases without any local discharge showed a great voltage dependence, meaning a major role of negative ion O @super -@ for oxidation. While under the negative DC biases the oxidation was rather small but the fairly large amount of the sputtering was observed at the voltage as small as 50 V, indicating the high chemical reactivity of O @super -@. In conjunction with the sputtering, however, it was observed that the sputtering became remarkable in a condition of oxidation saturation. On a basis of the oxidation depth obtained under these DC biases, directional oxidation was examined under low frequency RF bias of 100 kHz with a transformer couple to apply the net positive voltage for negative ion. This directional oxidation was made employing a Si sample of line and space with SiO@sub 2@ mask. It was demonstrated that the directional oxidation of1500A depth was possible under the RF bias of 25 W with 10 minute.

10:40am **PS-WeM8 Direct Measurement of VUV Caused Oxide Conduction during Plasma Charging**, ***J.P. McVittie***, Stanford University

In a plasma the local charging voltage of a floating structure is controlled by the difference in local electron and ion fluxes, the local capacitance and the feedback of the developed voltage on the local plasma sheath, which controls the electron current. Any additional discharging current paths will also affect the charging voltage and subsequent device damage. One such current path which is poorly understood is UV induced photoconductivity in dielectrics. Among of the problems in understanding this discharging path has been the difficulty in measuring dielectric conduction in a plasma and in separating charging from UV effects. In his work a very low density plasma was used to induced charging up to 20 V while a separate high density plasma separated by a thin filter/window was used to generate the vacuum UV. For monitoring charging a bare SPORT charging probes were used, and to monitor photoconductivity oxide covered probes were used. Conductivity which deceased linearly with the UV source power was observed. In addition, the conductivity deceased with 1/ oxide thickness squared. Finally, by using different filters it was concluded that VUV near the oxide band gap of ~9 eV was causing the conductivity. All these observations are consistent classic bulk induced photoconductivity. The implications of this dielectric conductivity on charging and related damage will be discussed.

11:00am **PS-WeM9 Vacuum Ultraviolet Spectra of Metal-Etch Plasma Processing Discharges**, ***J.R. Woodworth***, *M.G. Blain, R.L. Jarecki,* Sandia National Laboratories*; T.W. Hamilton,* Sandia National Laboratories, U. S. A*; B.P. Aragon,* Sandia National Laboratories, U. S. A.

We report measurements of the absolute fluxes of vacuum ultraviolet (VUV) photons to the wafer in a commercial aluminum-etch inductively coupled plasma processing tool for discharges containing chlorine, boron trichloride and argon. Most of the VUV emissions that we observed above 8 eV in these discharges were due to spectral lines of neutral chlorine atoms. Spectra and absolute fluxes as a function of rf power, substrate type, gas mixture, and pressure will be presented. This work was supported by the United States Department of Energy Under Contract No. AC04-94AL8500, by SEMATECH, and by Applied Materials. Sandia is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

11:20am **PS-WeM10 Spatial Characterization of Plasma VUV Emission in an ECR Etcher**, ***C. Cismaru***, *J.L. Shohet,* University of Wisconsin, Madison

In MOS (Metal-Oxide-Semiconductor) device fabrication, plasma processing plays an important role since it has many advantages in terms of process convenience, directionality and high resolution. However, because of the existence of charged particles, together with x-ray and vacuum ultraviolet emission, plasma processing enhances the possibility of damage of the processed materials. The damage potential of vacuum ultraviolet emission of processing plasmas on MOS devices is investigated. High energy photons, with energies higher than the energy band gap of SiO@sub 2@ (~9 eV) can be generated from recombination and relaxation processes in the plasma. It has been established that electron-hole pairs generated in the oxide by these photons@footnote 1@ will increase the SiO@sub 2@ bulk and Si/SiO@sub 2@ interface trapped-charge density, which will affect the device quality accordingly.@footnote 2@ In this work, emission spectra of various plasmas have been recorded in an ECR (Electron Cyclotron Resonance) etcher, at pressures ranging between 0.5 mTorr and 5 mTorr, and microwave powers between 700 W and 1000 W. The measurements were taken in the range of 20 Å to 3000 Å (600 eV to 4 eV), with a one-meter normal incidence vacuum monochromator, with a resolution of 0.2 Å. By use of a special reflection probe, the spectra were also recorded as a function of position across the wafer stage. The measurements show that most of the VUV emission of processing plasmas ranges above 9 eV, which may result in a potentially damaging effect on MOS devices. Also, a nonuniformity of the VUV photon flux impinging on the wafer surface as a function of position across the wafer has been found. This nonuniformity should be considered as having the potential for another MOS processing damaging factor. This work was supported in part by the National Science Foundation under Grant No. EEC 8721545. @FootnoteText@ @footnote 1@ R. A. Gdula, IEEE Transaction on Electron Devices 26(4), 644 (1979). @footnote 2@ R.J. Powell and G.F. Derbenwick, IEEE Transactions on Nuclear Science 18(6), 99 (1971).

Plasma Science and Technology Division
Room 318/319/320 - Session PS-WeA

Plasma-Surface Interactions I

Moderator: V.M. Donnelly, Bell Laboratories, Lucent Technologies

2:00pm **PS-WeA1 Surface Reactions and Hydrogen Coverage on Plasma Deposited Hydrogenated Amorphous Silicon and Nanocrystalline Silicon Surfaces, *D.C. Marra*[1]**, *S. Ramalingam, E. Edelberg, D. Maroudas, E.S. Aydil,* University of California, Santa Barbara

In situ attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy was used to study the H bonding on surfaces of amorphous hydrogenated silicon (a-Si:H) and nanocrystalline (nc-Si:H) films during plasma enhanced chemical vapor deposition (PECVD) from SiH@sub 4@/H@sub 2@/Ar containing discharges. During the deposition of a-Si:H films using SiH@sub 4@ without H@sub 2@ dilution, the surface coverage was primarily di- and trihydrides, and there were very few dangling bonds on the surface. In contrast, during the deposition of nc-Si:H using SiH@sub 4@ diluted with H@sub 2@, the amount of di- and trihydrides on the surface was drastically reduced and monohydrides dominated the surface. Furthermore, the vibrational frequencies of the monohydrides on nc-Si:H film match well with the resonant frequencies of monohydrides on H-terminated Si(111) and Si(001) surfaces. The decrease of higher hydrides upon H@sub 2@ dilution is attributed to an enhanced dissociation rate of tri- and di-hydrides on the surface through dangling bonds created by increased rate of H abstraction from the surface. The mechanism of hydrogen loss from the surface is thought to be abstraction by H and/or SiH@sub 3@ radicals. Simultaneously with the experiments, we have been using molecular dynamics (MD) simulations of radical-surface interactions occurring during PECVD of Si films. The MD simulations aim at the direct examination of chemical reactions, such as H abstraction by SiH@sub 3@ and by H as suggested by the analysis of the ATR-FTIR experiments. For example, using the MD simulations of deposition through SiH@sub 3@ impingement on the surface, we have observed that the dominant mechanism of H removal from the surface is through abstraction by SiH@sub 3@ radicals, which return subsequently to the gas phase in the form of silane. Atomistic simulation results will be presented together with experimental evidence for reactions that are thought to play key roles in plasma deposition of Si films.

2:20pm **PS-WeA2 Gas Phase and Surface Kinetics in Plasma Enhanced Deposition of Silicon Nitride: Effect of Gas Dilution on Electron Energy Distribution, Radical Generation, and Film Composition**, ***T.M. Klein***, *C.S. Yang, A.I. Chowdhury, G.N. Parsons,* North Carolina State University

Gas diluents, including N@sub@2, He, H@sub 2@, Ar, etc., are often used in silicon nitride plasma CVD to improve film density and electronic properties. We have formed silicon nitride films by parallel plate rf PECVD using SiH@sub 4@/NH@sub 3@ and SiH@sub 4@/N@sub 2@ source gases, and studied the effects of H@sub 2@, He, and N@sub 2@ dilution with substrate temperatures between 350 and 25°C. The plasma was characterized using optical emission and mass spectroscopy, and the thin films were characterized using infrared transmission, IV and CV measurements. We find that dilution can control the Si-H and N-H bond concentrations, and can improve the electrical performance in silicon nitride formed at very low temperature (35 at. %) at low temperature, resulting in high etch rates. Using SiH@sub 4@ and N@sub 2@ source gases, N/Si ratios > 1.3 can be achieved with hydrogen content < 20 at.%. However, optimized N/Si in the film is not obtained by simply increasing N@sub 2@ in the gas phase. At 12W and 250°C, increasing the N@sub 2@ gas fraction from 16% to 37%, leads to a decrease the N/Si in the film from 1.37 to 1.27. Using mass spectroscopy, the silane consumption fraction is greater than 90%, and significant change in silicon incorporation is not expected with N@sub 2@ dilution. We have modeled the effect of N@sub 2@ dilution on the electron energy distribution in the plasma using available software to solve the Boltzmann equation, and developed a simple gas kinetic model to estimate relative N and SiH@sub x@ radical concentrations. The model shows the high energy (>10eV) electron density decreases with N@sub 2@ dilution, consistent with the experiments. The model can predict the effects of gas residence time and He and N@sub 2@ dilution during nitride deposition from SiH@sub 4@/NH@sub 3@ mixtures. These results demonstrate a detailed understanding of gas dilution effects in plasma deposition, and indicate that optimized material properties can be predicted from detailed gas reaction analysis.

2:40pm **PS-WeA3 Atomistic Simulation of Plasma Enhanced Chemical Vapor Deposition of Hydrogenated Amorphous Silicon Films**, ***S. Ramalingam***, *D. Maroudas, E.S. Aydil,* University of California, Santa Barbara

Hydrogenated amorphous Si (a-Si:H) and microcrystalline Si grown by plasma deposition through SiH@sub 4@ containing discharges are widely used in solar cells and thin film transistors for flat panel displays. Developing deposition strategies for improving film quality requires a better fundamental understanding of the radical-surface interaction mechanisms. Atomic-scale computer simulations of the deposition process allow monitoring of the events that occur on the surface on a microscopic scale and help elucidate reaction mechanisms that lead to film deposition, defect formation and H incorporation. We present a systematic atomic scale analysis of the interactions of SiH@sub x@ (1@<=@x@<=@) radicals with pristine and H-terminated Si(001)-(2x1) surfaces as well as a-Si:H surfaces with varying H coverage. Hydrogen coverage of the surface is the key factor that controls both the surface reaction mechanism and the reaction probability. The radicals are most reactive when they impinge on pristine c-Si surfaces or surfaces of a-Si:H films with low H concentration, which have high density of Si dangling bonds. In contrast, they are less reactive on H-terminated c-Si and on a-Si:H films with high H coverage. Deposition of a-Si:H from SiH@sub 3@ radicals has also been simulated by repeatedly impinging SiH@sub 3@ radicals onto Si (001)-(2x1) surfaces. The key reactions that occur on the surface during the deposition can be grouped into three classes: (i) SiH@sub 3@ adsorption, (ii) H abstraction, and (iii) disilane formation. We have observed that the dominant mechanism of H removal from the surface is through abstraction by SiH@sub 3@ radicals, which return subsequently to the gas phase in the form of silane and leave behind a dangling bond. The dangling bond created upon H abstraction becomes an adsorption site for the SiH@sub 3@ radicals impinging at this location and the film grows by repeated abstraction and adsorption events which bring Si to surface and remove H.

3:00pm **PS-WeA4 The Ion-assisted Etching and Profile Development of Silicon in Molecular and Atomic Chlorine: Experiment, Modeling, and Simulation**, ***J.A. Levinson***, *E.S.G. Shaqfeh,* Stanford University; *M. Balooch, A.V. Hamza,* Lawrence Livermore National Laboratory

We report on an ion beam etching study designed to characterize the important kinetic and transport processes involved in the ion-assisted etching of silicon in both molecular and atomic chlorine. Monoenergetic argon ions were directed normal to a silicon wafer that was simultaneously exposed to a neutral molecular and/or atomic chlorine beam. Dissociation of the beam was induced by thermally heating the graphite tip of the effusive source via electron impact. Beam composition was characterized using a quadrupole mass spectrometer. Unpatterned polysilicon wafers were etched to determine the ion-induced etching yields as a function of ion energy, ion to neutral flux ratio, and neutral flux composition. A physically-based kinetic model was developed to represent the yield data. Feature etching experiments using patterned silicon wafers were also performed under ion-limited and neutral-limited conditions of varying neutral composition. Resulting profiles were examined for aspect-ratio dependent etching lag as caused by neutral starvation and/or atomic to molecular chlorine recombination. Computer simulations of the etching process and profile development were performed using the kinetic model and a line-of-sight re-emission model for the chlorine transport. The dependence of the yield on the ion angle of incidence was also incorporated into the simulation and was found to have a significant impact on profile evolution as a function of the ion to neutral flux ratio. Atomic to molecular chlorine recombination effects were explored as a function of the surface recombination coefficient. Predictions of the simulations were compared to experimentally-derived profiles.

3:20pm **PS-WeA5 The Role of Etching Products on the Chemical Composition and Thickness of the Chlorinated Surface Layer That Forms During Etching of Silicon in a Chlorine Plasma**, ***K.H.A. Bogart***, *V.M. Donnelly,* Bell Laboratories, Lucent Technologies

The influence of etching products on the surface layer formed during chlorine (Cl@sub 2@) plasma etching of unmasked and silicon dioxide (SiO@sub 2@) masked p-type Si (100) was investigated using vacuum-sample-transfer and angle-resolved x-ray photoelectron spectroscopy (XPS). The etch product concentration was controlled by varying the Cl@sub 2@ flow rate from 0.5 to 10.0 sccm at constant pressure. Gas phase Si, Cl, Cl@sub 2@, SiCl, SiCl@sub 2@, and SiCl@sub 3@ were

[1] **PSTD Coburn-Winters Student Award Finalist**

monitored by optical emission spectroscopy (OES). The Si etching rate increased linearly with Cl@sub 2@ flow from 1917 Å/min at 0.5 sccm to 2848 Å/min at 10 sccm. From these rates, mass balance, and the Si area (4.62 cm@super 2@), the product-to-etchant ratio, defined as SiCl@sub x@(g)/(Cl(g) + Cl@sub 2@(g)) varied from 3.64 to 0.027 between 0.5 and 10.0 sccm, respectively, and was qualitatively confirmed by OES. On unmasked substrates, Cl was present as SiCl@sub x@ (x = 1-3) at XPS Si2p@sub 3/2@ binding energies of 99.9, 101.0, and 102.0 eV, respectively, relative to Si at 99.1 eV. Surprisingly, the amounts of the three components and the total Cl (also derived from its 2p peak) were nearly independent of the product-to-etchant flux ratio. Depth profiles were obtained from an inversion of the observed take-off angle dependencies of the XPS signals. The chlorinated layer was approximately 20 Å thick, with Cl falling off in a graded fashion. The Cl areal density was 2.5 x 10@super 15@ Cl/cm@super 2@ and the average stoichiometry was [SiCl]:[SiCl@sub 2@]:[SiCl@sub 3@] = 1.0:0.25:0.20. SiCl@sub 2@ and SiCl@sub 3@ were in the top 75% of the layer, while SiCl was throughout the layer. On SiO@sub 2@ masked samples, less SiCl@sub x@ was found on exposed Si sidewalls, as well as on trench bottoms, than on unmasked samples. SiCl@sub x@ coverage in the features was also independent of the product-to-etchant flux ratio, suggesting that redeposition of SiCl@sub x@ plays no role in etched profile evolution.

3:40pm **PS-WeA6 Reactive Ion Etching of Si by Cl, Cl@sub 2@, and Ar Ions: Molecular Dynamics Simulations with Comparisons to Experiment**, ***D.E. Hanson****, J.D. Kress, A.F. Voter,* Los Alamos National Laboratory

We will present results of molecular dynamics simulations of reactive ion etching (RIE) of a reconstructed Si(100)(2x1) surface. The existing Stillinger-Weber Si/Cl interatomic potential has been modified by correcting the Si-Si bond strength for a SiClx moiety bound to a Si surface as a function of the number of Cl atoms, x. This potential has been used to study RIE of Si by Cl, Cl@sub 2@ and Ar ions to characterize the Si yield, product stoichiometry, and the stoichiometry of the chlorosilyl surface layer as a function of ion energy and species. Such results, suitably parameterized, can be used as fundamental input to device feature scale topography simulations. We have also simulated the dissociative chemisorption of Cl@sub 2@ on Si(100)(2x1) and find that it is in reasonable agreement with experiment. We will discuss an important area of disagreement between theory and experiment, the effect of neutral to ion ratio on the Si yield. Where possible, we will present comparisons of our results with experiment. @FootnoteText@ Work partially supported by Cooperative Research and Development Agreement between the US Department of Energy and the Semiconductor Research Corporation.

4:00pm **PS-WeA7 Investigation of Si-poly Etch Process for 0.1 µm Gate Patterning and Beyond**, ***L. Vallier,*** France Telecom-CNET, France*; L. Desvoivres, M. Bonvalot,* France Telecom-CNET*; O. Joubert,* France Telecom-CNET, France*; S. Tedesco, B. Dal'Zotto,* CEA-LETI, France

The etching of dense and isolated 0.1µm gate structures has been studied in a high density plasma helicon source capable of processing 200 mm diameter wafers. The gate stack consists of 150 nm thick amorphous silicon film on a 2 nm thick gate oxide, covered with 50 nm thick SiO@sub 2@ patterns obtained using e-beam direct writing. HBr/O@sub 2@ gas chemistry is used for the etching; a 2 steps etching recipe using 2 RF bias regimes was developped in order to obtain anisotropic etching profiles without any etching anomalie(trenching, bowing, notching) while keeping a high selectivity on the very thin gate oxide. Real time ellipsometry was used either to measure etching rates or to monitor the arrival on the thin gate oxide. XPS analysis of the etched wafer is performed in an ultra high vacuum chamber after transfer under vacuum ; XPS data were obtained on dedicated structures with different aspect ratio allowing the gate oxide comsumption as well as sidewall passivation thickness to be precisely measured in dense areas. Attempts to measure CD variation due to the etch process and profiles anomalies related to the etching parameters will also be presented. @FootnoteText@ This work has been carried out within the GRESSI Consortium between CEA-LETI and France Telecom-CNET

4:20pm **PS-WeA8 Mechansims in High Aspect Ratio Oxide Feature Etching using Inductively Coupled Fluorocarbon Plasmas**, ***M. Schaepkens****, G.S. Oehrlein,* State University of New York, Albany*; K.G. Donohoe,* Micron Technology, Inc.*; J.M. Cook,* Lam Research Corporation

Mechanisms controlling SiO@sub 2@ etching in high aspect ratio features have been studied using an inductively coupled plasma (ICP) source fed with trifluoromethane (CHF@sub 3@) gas. The behavior of the transition from fluorocarbon deposition to SiO@sub 2@ etching with increasing self-bias voltage has been determined in features with aspect ratios ranging from 0.8 to 6. Both the fluorocarbon deposition rate on the feature bottom at 0 W bias and the SiO@sub 2@ etching rate at highly negative self-bias voltages decrease with increasing aspect ratio. The SiO@sub 2@ etch rate reduction can be explained by a differential charging mechanism, for which experimental evidence is provided. Surface chemistry results obtained in microstructures are compared with unpatterned surfaces, and their significance for the etching process is discussed.

4:40pm **PS-WeA9 Surface Reactivity of CF and CF@sub 2@ Radicals Measured Using Laser-Induced Fluorescence and CHF@sub 3@ Plasma Molecular Beams**, ***N.E. Capps****, N.M. Mackie, E.R. Fisher,* Colorado State University

Fluorocarbon discharges have been widely studied because of their ability to promote etching of a variety of substrates and to deposit a wide range of fluorinated polymeric films. CF and CF@sub 2@ radicals are important species in fluorocarbon pla smas and are postulated to contribute both to plasma polymerization and to selective etching of Si and SiO@sub 2@. The surface reactivity of CF and CF@sub 2@ radicals during the plasma processing of a variety of substrates using the Imaging of Radicals I nteracting with Surfaces (IRIS) technique is reported. IRIS combines spatially-resolved laser-induced fluorescence with molecular beam and plasma techniques. The molecular beam source is a 100% CHF@sub 3@ plasma, and we have investigated the surface rea ctivity of CF and CF@sub 2@ with silicon. silicon dioxide, silicon nitride, 304 stainless steel, and system 8 photoresist. Surface reactivity measurements were determined under a range of plasma powers, with ambient and heated surfaces, as well as under low and high ion bombardment conditions. On all surfaces we see generation of CF@sub 2@ radicals whereas CF radicals are consumed at the surface under similar plasma conditions. Mechanisms for film formation and for the surface production of CF@sub 2@ will be discussed

5:00pm **PS-WeA10 Optical Monitoring of Surface Adlayers by Laser-induced Thermal Desorption during Plasma Etching of Si and Ge**, *J.Y. Choe,* ***I.P. Herman****,* Columbia University*; V.M. Donnelly,* Bell Laboratories, Lucent Technologies

Laser-induced thermal desorption, with detection by laser-induced fluorescence (LD-LIF) and transient plasma-induced emission (LD-PIE), was used to analyze the surface during the chlorine plasma etching of Si and Ge in an inductively-coupled plasma (ICP) source. Quantitative information about the formation and ion-induced removal of this surface layer was obtained from the optical signals. A pulsed XeCl excimer laser (308 nm) was used to desorb the surface layer and (for LIF) to excite the desorbed species. LD-LIF was used to probe SiCl (292.4 nm) and GeCl (289.12 nm) to compare Si and Ge etching. The surface adlayer did not change with ion density for both Si and Ge, but the rate of adlayer chlorination for Ge was much faster (< 0.1 s) than that for Si (~ 5 s), as was indicated by the signal size when the laser repetition rate was varied. The chlorine content of the adlayer did not change with ion energy (16 - 116 eV) during Ge etching, as confirmed by XPS analysis; in contrast, for Si the adlayer became more chlorinated with increasing ion energy. The etch yield for ion sputtering from Ge increased from 1 to 3 atoms/ion from 16 to 116 eV ion energy. LD-PIE was also used to probe SiCl, SiCl@sub 2@, and Si atoms during Si etching. No LD-PIE signal from Cl or Cl@sub 2@ was detected, suggesting that steady-state chlorine desorption is negligible during the plasma etching of Si. LD-LIF and LD-PIE signals during Si etching by Cl@sub 2@ have been compared for various processing conditions. The work at Columbia was supported by NSF grant DMR-94-11504.

Electronic Materials and Processing Division
Room 314/315 - Session EM+PS-ThM

Processing of High K Dielectrics for DRAMs

Moderator: K.R. Milkove, IBM T.J. Watson Research Center

8:20am **EM+PS-ThM1 Growth and Characterization of Ba@sub 0.6@Sr@sub 0.4@TiO@sub 3@ Thin Films on Si with Pt Electrodes**, ***L. Kinder***, *I.L. Grigorov, C. Kwon, Q.X. Jia,* Los Alamos National Laboratory*; L. Luo, J. Zhao,* Applied Materials, Inc.

The application of high dielectric constant materials like barium strontium titanate in dynamic random access memories requires the integration of these materials into the existing Si technology. In this study, pulsed laser deposition was used to grow Ba@sub 0.6@Sr@sub 0.4@TiO@sub 3@ (BST) thin films on Si with Pt electrodes. Through scanning electron microscopy, x-ray diffraction, and electrical characterization, the Pt/BST/Pt capacitor processing on Si has been optimized. BST films on Pt sputtered at high power tends to show high leakage current. However, high leakage current is prevented if the Pt is sputtered at low powers. Low power deposition leads to not only smooth Pt film but also less hillocks. The smoother Pt electrodes allow the BST to grow with greater crystallinity. 150 nm BST on Pt shows a dielectric constant over 400 and dielectric loss of 0.01 at 10 kHz. The quality of the dielectric can be further improved by first depositing a thin seed layer of BST at lower temperatures. We have successfully used 20 nm BST deposited by metal-organic chemical vapor deposition as a seed layer to improve the over all device performance. The influence of interface and of initial nucleation of BST films on the structural and dielectric properties of the thin film capacitors will be also discussed.

8:40am **EM+PS-ThM2 Synthesized Single Crystalline Ba@sub (1-x)@Sr@sub x@TiO @sub 3@ Thin Films for DRAM Application**, ***F.F. Feng***, University of Houston*; C.L. Chen, Z.H. Zhang,* University of Houston, U. S. A.*; Y. Liou, P. Jin,* University of Houston*; W.K. Chu,* University of Houston, U. S. A.*; C.W. Chu,* University of Houston

Perovskite Ba@sub (1-x)@Sr@sub x@TiO@sub 3@ thin films have been synthesized on (001) LaAlO@sub 3@ and (001) SrTiO@sub 3@ substrates with SrRuO@sub 3@ or Pt bottom electrodes by pulsed laser ablation. Extensive X-ray diffraction, rocking curve, and pole-figure studies suggest that the as-grown films are (00l) oriented with single crystalline quality. RBS studies indicate that the epitaxial films have excellent crystalline quality with an ion beam minimum yield of only 2.6 % or less, suggesting that the crystallinity of the as-grown films can be compared with the single crystal silicon. Atomic force microscopy studies indicate that the as-epitaxial films are atomic smooth under the selected growth conditions. The dielectric property measurements show room temperature values of the relative dielectric constant and loss tangent of larger than 750 and 0.005, respectively.

9:00am **EM+PS-ThM3 Scanning Capacitance Imaging for Evaluation of High-k Dielectric Oxide Materials**, *Y. Yamaguchi, K.P. Wiederhold, B.D. White, N.E. Wittry,* ***H.C. Galloway***, Southwest Texas State University

We have used scanning capacitance imaging to measure the dielectric properties of oxide materials such as BST which have large dielectric constants (high-k). These materials are of interest as potential replacements for the dielectric in memory devices due to their increased capacitance per unit area. Several scanning capacitance methods have been developed using modified atomic force microscopes and they are actively used to measure quantities such as the thickness of SiO@sub 2@ layers or the doping levels across a p-n junction. We will discuss how this technique can be used as a diagnostic tool when applied to the high-k oxides. First, the measurement of the dielectric properties on a local scale may help to identify the causes of failure modes in materials. As an example, we will report on local variations of the dielectric constant observed in films of BST grown by RF planar magnetron sputtering. Second, we have used scanning capacitance to evaluate films of novel oxide materials grown by Dual Ion Beam Sputtering.@footnote 1@ The advantage of Scanning Capacitance Microscopy is that the relative merits of different growth conditions can be rapidly assessed and compared to each other or to a reference standard. This allows us to investigate new materials or deposition conditions without having to form complete devices for analysis. By identifying the most promising growth conditions that yield high dielectric constants, uniform films, and low leakage currents we can speed up the process of testing new growth methods and materials.

@FootnoteText@ @footnote 1@P. Perera, R. Selestino, and C.J. Gutierrez, Department of Physics, Southwest Texas State University

9:20am **EM+PS-ThM4 Characterization of Thermal Annealing of Tantalum Pentoxide for High-k Dielectric Applications**, ***R.L. Opila***, *J.P. Chang, G.B. Alers,* Bell Laboratories, Lucent Technologies

Tantalum pentoxide is being studied as an alternative high dielectric constant material for storage capacitors or gate dielectrics. Since the oxide layers are thin, even for high dielectric constant materials, interfaces between the tantalum pentoxide and other thin film materials can greatly affect device electrical properties. This paper focuses on analyzing the bulk properties of the Ta@sub 2@O@sub 5@ film and the Ta@sub 2@O@sub 5@/TiN interface to assess a new TiN/Ta@sub 2@O@sub 5@/TiN storage capacitor structure that has lower contact resistance and higher specific capacitance than conventional poly-Si based capacitors. The effect of thermal annealing on the electrical performance of the capacitor will be presented. Angular Resolved X-ray Photoelectron Spectroscopy (ARXPS) has been used to characterize the interfacial composition and stoichiometry of tantalum pentoxide deposited by CVD processes at low temperatures. The amount of carbon incorporated in the film during the CVD process decreases with increasing process temperature. Reduced leakage current has been observed as the concentration of carbon in the film increases. Formation of TiO@sub 2@ was observed at the Ta@sub 2@O@sub 5@/TiN interface at an RTA temperature of 450°C. Significant amounts of titanium suboxides are also observed at the Ta@sub 2@O@sub 5@/TiN interface. The imperfect interface is thought to reduce the specific capacitance and increase leakage currents, perhaps through partial reduction of the Ta@sub 2@O@sub 5@. Correlation between the interface chemical states and the electrical performance will be presented.

9:40am **EM+PS-ThM5 Structural Properties of Ultrathin Films of High Dielectric Constant Materials on Silicon**, *E. Gusev,* IBM T.J. Watson Research Center*; H.C. Lu, T. Gustafsson,* ***E. Garfunkel***, Rutgers University*; G.B. Alers,* Bell Laboratories, Lucent Technologies

The high tunneling rates in ultrathin gate oxides is driving the search for higher-K replacement dielectrics in silicon microelectronics. Ta@sub 2@O@sub 5@ and several other metal oxides are now attracting the attention of the device community. One problem that plagues the use of metal oxides on Si is the formation of an interfacial SiO@sub 2@ layer; such layers limit the capacitance and can degrade the electrical properties of the gate structures. We have examined the composition of interfacial layers of several high dielectric constant oxide systems using high resolution medium ion energy scattering. We find that the interfacial region is best described as neither Si/SiO@sub 2@/metal-oxide nor Si/metal-oxide, but can be viewed as a compositionally graded oxide with a dielectric constant significantly higher than that of pure SiO@sub 2@ (as inferred from electrical measurements). Annealing changes the near-interfacial composition substantially. When post anneal temperatures are kept low, stable composite oxide structures (with physical thickness greater than 7nm) can be obtained that demonstrate good electrical properties and an effective SiO@sub 2@ thickness of less than 2 nm.

10:00am **EM+PS-ThM6 Etching of High Dielectric Constant Materials for DRAMs and Ferroelectric Materials for FeRAMs**, ***L.G. Jerde***, *A. Cofer, K. Olson, P. Rajora, S.P. DeOrnellas,* Tegal Corporation **INVITED**

The introduction of ferroelectric and high dielectric constant films and their associated metals, barrier materials and adhesion layers for DRAM, embedded DRAM and FeRAM applications are driving some of the most challenging etch requirements in the IC fabrication industry. The specifications resulting from these requirements range from very aggressive profile and critical dimension control, to etch selectivities, contamination and damage, defects and chamber cleaning frequency. Some of the most difficult of these requirements are a result of the design rules that will be used in production for the DRAM applications (i.e., 0.15 m and below). The inherent involatility of the etch products of these materials is another key factor contributing to the difficulty in meeting the requirements. In this paper we will present and discuss the etch requirements for these materials, the reactor technology we use to etch them, selected process and manufacturability results for these materials and future directions for this work.

10:40am **EM+PS-ThM8 Patterning of Reactively Sputtered Tantalum Pentoxide, a High Epsilon Material, by Plasma Etching**, *L.B. Jonsson, F. Engelmark, J. Du, C. Hedlund,* Uppsala University, Sweden*; U. Smith,* Ericsson Components AB, Sweden*;* ***H.-O. Blom****,* Uppsala University, Sweden

The large size of integrated capacitors is a problem today. The capacitors can easily cover a major part of the total chip area. By using a high epsilon material as the dielectric material in the capacitor the size can be reduced significantly. One very promising candidate is Tantalum pentoxide (Ta@sub2@O@sub5@) which has an epsilon of 25 compared to Silicon dioxide which has 3.9. In order to make integrated capacitors the Tantalum pentoxide must be patterned. We have investigated and optimized dry etching processes for realizing a complete capacitor structure. One process for etching the Tantalum pentoxide on a back contact made of poly-silicon and one process for etching contact holes, in silicon dioxide, down to the Tantalum pentoxide. Data from Reactive Ion Etching (RIE) as well as for Inductively Coupled Plasma (ICP) processes will be presented.

11:00am **EM+PS-ThM9 The High Temperature Platinum Etching Using Titanium Layer**, ***H.-W. Kim****, B. Ju, B. Nam, W. Yoo, C.J. Kang, T.-H. Ahn, J. Moon, M.Y. Lee,* Samsung Electronics, Co., Korea

1. Introduction: It is necessary to use the platinum as a bottom electrode material of the BST capacitor in highly integrated deveces, however, the Pt etching of the fine patterns is difficult due to the inherent non-reactivity of platinum. It is revealed that the Pt etch slope of 80° was attained by O@sub 2@/Cl@sub 2@ chemistry by elevating the substrate temperature up to 160°C. This result is thought to be due to the reaction of O species with Ti layer and analyzed by TEM, XPS and AES. 2. Experimental & Results: As an experimental setup for high temperature etching, the modified chiller using Galden HS260 (B.P.=270°C) was chosen. The oxide 5000Å/ Ti600Å/ Pt 2000Å structure was used and the O@sub 2@/Cl@sub 2@ (O@sub 2@ = 80%) gas was chosen as an etchant combination in MERIE system. The change of the Pt etching profile at 100°C, 130°C, 160°C, respectively was investigated.The Pt etch slope does not depend on the substrate temperature up to the just etch time, the etch slope of the 160°C-sample was about 80° after 100% overetch and the Ti mask was not eroded significantly. It appeared that the titanium mask of 100°C, 130°C samples were eroded considerably, The Pt etching results of 160°C with Ti, TiN and TiO@sub 2@ layer were compared (not shown). TiN and TiO@sub 2@ layer does not help attaining high Pt etch slope even with the thermal heating. From the above result, it is surmised that the change or stabilization of Ti layer through the reaction/diffusion of O atoms during plasma etching plays a major role in attaining the higher Pt etching slope. From the XTEM investigation of the 160°C-etched one, the center of the Ti layer stays crystalline, however, the edge of the Ti layer became amorphous and the oxygen content increased up to more than 50%, by EDX analysis. The XPS analysis of 100-Ti layer showed that the considerable amount of Ti-Ti bond changed to the Ti-O bond during the O@sub 2@/Cl@sub 2@ plasma treatment. The AES analysis confirmed the above phenomena. 3. Conclusions: The etching slope of Pt was improved by the reaction of the mask material with the etching species, not by the reaction of Pt itself. The optimal overetching helps to attain the higher etch slope as long as the Ti mask stays. High temperature processing helped the duration of the titanium mask by activating the reaction of Ti with O-species.

11:20am **EM+PS-ThM10 Removal of Sidewall Re-depositions Formed by Reactive Ion Etching of Platinum for Embedded DRAM Applications**, *H.M. Ranpura, D.H. Butler,* ***S.P. Beaudoin****,* Arizona State University*; C.J. Tracy, L. Chang,* Motorola Semiconductor Products Sector

Removal of platinum sidewall re-depositions (SRDs) formed due to patterning of electrodes due to reactive ion etching (RIE) for an embedded dynamic random access memory (DRAM) project has been investigated. A serious problem in integrating these devices is the re-deposition of non-volatile etch products onto the pattern sidewall. Removal of these SRDs without damaging other exposed materials is a challenging process. A mixture of argon (Ar) and chlorine (Cl@sub 2@) plasma was used to etch the platinum electrodes. Following the etching step the wafers were processed in an oxygen plasma to remove the photoresist on the wafer. Results are presented for post-ashed wafers that were heated at different temperatures for varying times in different ambients. Following heating wafers were cleaned in aqueous hydrochloric acid (HCl). Results are also presented for ultrasonic cleaning of wafers in HCl.

11:40am **EM+PS-ThM11 Study on Surface Reaction of (Ba,Sr)TiO@sub 3@ Thin Films by High Density Plasma Etching**, ***S.B. Kim****, C.I. Kim, E.G. Chang,* Chung-ang University, Korea

Ferroelectric devices are attractive for dynamic random access memories (DRAMs) applications because of high dielectric constant. Using ferroelectric device structure, manufacturing cell capacitance of highly integrated memory device is possible. Small feature size requires anisotropic etching. Since research of (Ba,Sr)TiO@sub 3@ thin films etching is not widely, we studied on surface reaction of (Ba,Sr)TiO@sub 3@ thin films by high density plasma etching. (Ba,Sr)TiO@sub 3@ thin films were etched with an Inductively coupled plasma (ICP) by varying the etching parameter such as BCl@sub 3@/C@sub 2@F@sub 6@/Ar gas mixing ratio, RF power, and pressure. Etching effect were investigated in terms of etch rate, selectivity. In this study, (Ba,Sr)TiO@sub 3@ etching mechanism was investigated with XPS (X-ray photoelectron spectroscopy) and OES (Optical emission spectrometry) and QMS (Quadrupole mass spectrometry). Ion current density was measured by using single Langmuir probe. Surface of etched (Ba,Sr)TiO@sub 3@ investigated with SEM (Scanning electron microscopy).

Plasma Science and Technology Division
Room 318/319/320 - Session PS-ThM

Plasma Applications in Copper Metallization

Moderator: D.B. Graves, University of California, Berkeley

8:20am **PS-ThM1 Plasma Processes for Copper Dual Damascene Interconnect in Advanced CMOS Technologies**, ***J.E. Heidenreich****, D. Edelstein, R. Goldblatt, W. Cote, C. Uzoh,* IBM - Semiconductor R & D Center*; T. McDevitt, A. Stamper,* IBM Microelectronics*; A.H. Simon,* IBM - Semiconductor R & D Center*; J. Dukovic,* IBM T.J. Watson Research Center*; R. Wachnik, H. Rathore,* IBM - Semiconductor R & D Center*; S. Luce, J. Slattery,* IBM Microelectronics*; J. Ryan,* IBM - Semiconductor Research and Development Center **INVITED**

IBM has announced the implementation of Copper interconnect for a sub-0.25µm CMOS technology.@footnote 1@ This technology uses up to 6 levels of Copper wiring with a minimum metal contacted pitch of 0.63µm. Copper metalization offers the advantages of upto 40% reduction in wire resistance, increased allowable current density, and increase scalability, relative to Ti/Al(Cu) wiring which is commonly used in semiconductor applications. This technology was produced using a Dual Damascene integration scheme that dramatically reduces the number of steps necessary to build wiring levels. The industry, as a whole is moving toward both Copper metalization and Dual Damascene integration for reduced cost and increased performance. This talk will review the characteristics of this technology, and the results of our reliability evaluation. It will also focus on some of the special plasma processing challenges and opportunities that arise with the use of Dual damascene and Copper. @FootnoteText@ @footnote 1@D. Edelstein et al., Proc. IEEE IEDM, 773 (1997).

9:00am **PS-ThM3 Low k Dielectric Etching in High Density Plasmas**, ***O. Joubert****,* France Telecom CNET/DTM/TFM, France*; L. Vallier, P. Czuprynski,* France Telecom CNET, France

Dielectric etching remains one of the most challenging etching process for ultra large scale integration (ULSI) technology. The need to move to the so-called low k dielectric materials open a all new area of investigation. Among different options, one is to use polymers as low k dielectric. Opening high aspect ratio contact holes in polymer type materials can be as challenging as opening high aspect ratio contact holes in SiO@sub 2@. In this paper we have been studying the etching of high aspect ratio contact holes (higher than 5) in polymers. Studies were performed in a high density helicon source using various chemistries and plasma operating conditions. The etching was controlled using real time ellipsometry and optical emission techniques. First, oxygen plasmas were tentatively used to open high aspect ration contact holes. In all the plasma operating conditions used (low density and high density regimes and always at very high chuck bias power), undercut due to spontaneous etching reactions between the polymer and oxygen atoms present in the discharge or profile deformation such as bowing were observed. Other chemistries such as H@sub 2@/N@sub 2@ gas mixtures where spontaneous etching reactions between the polymer and reactive species are less important were also investigated. Oxygen based chemistries such as O@sub 2@/CO, O@sub 2@/CH@sub 4@, O@sub 2@/SO@sub 2@ allowing passivation layers to be formed on the polymer sidewalls of the contact were investigated. The

best contact hole profiles were obtained using O@sub 2@/SO@sub 2@ gas mixtures where sulfur deposition on the polymer sidewalls strongly minimizes spontaneous etching reactions. On the other hand, some sulfur-based species are left behind which can react with air moisture possibly inducing metal corrosion during the subsequent interconnect formation. In situ anticorrosion treatments were performed to remove sulfur based species. The anticorrosion efficiency was evaluated by measuring the sulfur concentration on all the contact hole surfaces before and after anticorrosion treatment using chemical topography analyses by x ray photoelectron spectroscopy (XPS). @FootnoteText@ This work has been carried out within the GRESSI consortium between CEA-LETI and France Telecom-CNET.

9:20am **PS-ThM4 High Density Plasma Patterning of Organic Low Dielectric Constant Materials***, **T.E.F.M. Standaert**, P.J. Matsuo, S.D. Allen,* State University of New York, Albany*; K.H.J.M. Robben,* Eindhoven University of Technology, The Netherlands*; G.S. Oehrlein,* State University of New York, Albany*; J.G. Langan, W.R. Entley,* Air Products and Chemicals, Inc.*; R. Gutmann, T.M. Lu,* Rensselaer Polytechnic Institute

We have studied the etching of several organic low dielectric constant materials in a Transformer Coupled Plasma (TCP) source employing in-situ diagnostics, such as ellipsometry, x-ray photoelectron spectroscopy (XPS), and optical emission spectroscopy (OES). Dielectrics of particular interest are Polyarylene ether (PAE-2) and Parylene-N. Etched microstructures were examined by scanning electron microscopy (SEM). Successful pattern transfer into these organic dielectrics has been demonstrated using an Ar/O@sub 2@ chemistry and a SiO@sub 2@ hard mask. A systematic study has revealed how the erosion of the sidewall can be controlled as a function of the oxygen radical and ion flux. Following the dielectric etch, characterization of the surface residues and modifications were performed. The efficiency with which the original underlayer surface can be recovered was also investigated.

9:40am **PS-ThM5 Plasma Deposition of Low-Dielectric-Constant Fluorinated Amorphous Carbon Interlayer Dielectrics***, **K. Endo**,* NEC Corporation, Japan **INVITED**

As LSI circuits continue to shrink, delay time of wiring caused by parasitic capacitance of interconnects becomes more important and further reduction becomes more difficult. Low-dielectric-constant (low-k) interlayer dielectrics (IL D) and low resistively wiring metals are now promising for reducing the RC delay of interconnects. Polymers are promisin g low-k materials. However, poor adhesion with Si substrates, poor thermal stability, and production difficulties have h indered their use in microelectronics. On the other hand, plasma-enhanced chemical vapor deposition (PE-CVD) of polymer films has many advantages that overcome these problems. Recently, a use of low-k fluorinated amorphous carbon (a-C:F) fi lms, that have both crosslinked and PTFE (polytetrafluoroethylene)-like structures, has proposed.@footnote 1@ Now, a cla ss of materials is widely investigated using PE-CVD. Around 400°C thermal stability and the dielectric constant o f 2.3-2.7 are realized by controlling the fluorine concentration in the films. For an easier integration, a-C:F film is covered with SiO@sub 2@ that protect the a-C:F film during processing. Si-rich SiO@sub 2@ glue layer is used to maintain adhesion strength between them. Also, excellent gap filling was realized by u sing a biasing PE-CVD technique. The fabrication of globally planarized 3-lebel Al interconnect using a-C:F ILD achieved 50% reduction in capacitance. Now, a combination of Cu and low-k materials is most promising for the further reduction in RC delay. Also, lower deposition temperature of Cu is appropriate for the low-k materials that are typically less the rmally stable than SiO@sub 2@ films. The a-C:F deposition technology can also be applied to Cu wiring system. A damascen e structure with Cu wiring and a-C:F ILD was successfully fabricated and no reaction between Cu and fluorine was observe d. @FootnoteText@ @footnote 1@K. Endo, MRS Bulletin 22, 55 (1997).

10:20am **PS-ThM7 Sources of Asymmetry in Ionized Metal PVD Reactors@footnote 1@***, **J. Lu**, M.J. Kushner,* University of Illinois, Urbana-Champaign

Ionized metal physical vapor deposition (IMPVD) can produce highly ionized metal fluxes for use in filling high-aspect-ratio vias and trenches in microelectronic devices. A typical IMPVD reactor uses inductively coupled plasma (ICP) excitation in conjunction with a dc or rf magnetron. Directionality, uniformity, and high deposition rate are the most desired properties in the deposition process. One factor that significantly affects the cited properties is the symmetry of excitation and sputtering in the IMPVD reactor. Asymmetries may be caused by nonuniform erosion of the target, asymmetric gas injection and/or pumping, or non-uniformities in the inductively coupled field due, for example, to transmission line effects. These asymmetric processes couple nonlinearly with each other. In this paper, sources of asymmetry in metal deposition will be numerically investigated. The computational tool used in this study is the three-dimensional Hybrid Plasma Equipment Model (HPEM), in which a Monte Carlo sputter model is coupled self-consistently to the plasma simulation. The reactor being modeled uses an external coil (made possible by a Faraday shield). Typical operating conditions are 10 mTorr gas pressure, 1kW ICP power, and 13.6MHz frequency. The uniformity of the ion flux and ionization fraction for Cu and Al IMPVD systems will be discussed as a function of aspect ratio, target geometry and antenna design. @FootnoteText@ @footnote 1@Work supported by SRC, Materials Research Corporation, and NSF.

10:40am **PS-ThM8 Simulations for Process Optimization Issues in Ionized Metal PVD***, **P.L.G. Ventzek**, M. Hartig, V. Arunachalam, D.G. Coronell, D. Denning,* Motorola Inc.

Magnetron plasma sources for ionized metal plasma physical vapor deposition (IMP-PVD) are being exploited for metal deposition in semiconductor device manufacturing applications because of their ability to lay down films with the required step coverage at high rates and reasonable uniformity. Challenges exist to extend the technology to ever more aggressive features with tighter tolerances on process parameters (e.g. uniformity). Despite their importance, multidimensional numerical models that treat the plasma dynamics in IMP chambers are relatively rare. This is possibly due to the difficulty in considering the complex magnet arrangements that characterize these systems. In this paper, we will present results obtained using the Hybrid Plasma Equipment Model (HPEM)@footnote 1@ and MAXWELL3D@footnote 2@ to simulate the behavior of a generic IMP source for metal deposition. This generic source employs internal coils to ionize metal sputtered from a target in a dc magnetron. As is typical, the dc magnetron structure is azimuthally asymmetric and will consist of concentric spirals of oppositely oriented permanent magnets. A special feature of the model is that energy and angle dependencies in the sputter yield are considered and that we have developed a methodology for looking at 3- dimensional effects.@footnote 3@ First we will present design-of-experiment studies of various process parameters and magnet configurations. In general, reasonable agreement has been found between ion fluxes to the target and experimentally determined erosion profiles. Second we will illustrate how various process parameters affect across wafer thickness uniformity, compositional uniformity and step coverage. @FootnoteText@ @Footnote 1@M. Grapperhaus et al., J. Appl. Phys., 83, 39 (1998) @Footnote 2@Ansoft Corp. @Footnote 3@see AVS paper by J. Kress et al.

11:00am **PS-ThM9 Modeling of IMP Copper for Electroplating Seed Layer Application***, **H.M. Zhang**, I. Hashim, P.J. Ding, B. Chin, J.C. Forster,* Applied Materials

Copper is being considered for semiconductor metallization because of its better conductivity, and higher electromigration resistance compared to aluminum. Current trends suggest that electroplating will be the primary choice for copper deposition in sub-0.25 µm generations because of its relatively low cost, high deposition rates, and ease of filling high aspect ratio features. However a conducting seed layer is required prior to electroplating. Ion-metal-plasma (IMP) deposition of copper has been demonstrated to provide a good seed layer for aspect ratios up to 4.5 :1.@footnote 1@ To meet the challenges of filling even higher aspect ratio features, a better understanding of both the electroplating and IMP process is required. In this paper, we will focus on extending the limits of the IMP copper deposition process by using simulations. A 2-dimensional hybrid plasma equipment model (HPEM),@footnote 2@ developed at the University of Illinois, is used to model the IMP Cu system. Simulation results of the deposition rate show good agreement with experimental data. The ionization ratio of copper can be increased by increasing the RF power or the process pressure. TEM analysis of IMP copper deposition into high aspect ratio features show a significant improvement of the step coverage at higher pressures. A good correlation was obtained between ionization fraction predicted by simulation and experimentally obtained bottom coverage measurements. This study will show that with proper optimization, the application of IMP Cu to the deposition of seed layers for electroplating can be extended to future generation and geometries. @FootnoteText@ @footnote 1@I. Hashim et al, Abstract submitted for VLSI Multilevel Interconnection Conference, 1998. @footnote 2@M. Grapperhaus and M.J. Kushner, J. Applied Physics., 81, 569 (1997)

11:20am **PS-ThM10 Metal Flux Ionization Fraction in Copper Ionized Physical Vapor Deposition@footnote 1@**, *T.G. Snodgrass, J.E. Foster, S. Lu,* ***A.E. Wendt****, J.H. Booske, J.L. Shohet,* University of Wisconsin, Madison

A characterization and modeling effort is directed at a more complete understanding of the potential and limitations of copper ionized physical vapor deposition (IPVD) for damascene processes. An rf inductively-coupled IPVD tool operating in argon includes a dc magnetron sputter source mounted in the top of an 18" D chamber. A 14'' D internal single-turn rf induction antenna is positioned between the magnetron and a 12" D substrate holder. Improved filling of high aspect-ratio features depends on the degree to which metal atoms are ionized as they pass through the rf plasma. To identify factors governing the "ionized flux fraction," measurements of metal properties have been made in the gas phase and at the substrate. Optical spectroscopy and Langmuir probes measure gas phase concentrations of neutral and ionized copper, and an improved quartz crystal microbalance@footnote 2@ is used to determine both neutral and ion fluxes at the substrate. The sputter rate from the target as well as the deposition rate radial profile at the substrate location have been characterized in detail. Results with and without the rf plasma show that the rf induction plasma has the primary effect of increasing the ionized metal flux and has only a minor effect on the flux of neutral copper. Selfsputtering of the internal rf antenna has also been examined, and methods to control it will be presented. A model has been constructed that, along with the measurements described, provides a physical explanation of the IPVD operating characteristics. @FootnoteText@ @footnote 1@This work supported by NSF grant #EEC8721545 @footnote 2@T. G. Snodgrass, W. Wang, J. H. Booske, A. E. Wendt, J. L. Shohet, submitted to Rev. Sci. Instr.

11:40am **PS-ThM11 Scattering and Sputtering Processes of Energetic Ar@super +@ and Cu@super +@ Ions on Cu Surfaces: Molecular Dynamics Simulations**, ***C.F. Abrams****, D.B. Graves,* University of California, Berkeley

Two competing technologies, electroplating and ionized PVD, show promise in filling narrow, high aspect ratio trenches and vias with copper. While energetic metal and inert gas ions play central roles in IPVD, they are potentially no less important in plating due to the need to deposit a high-quality seed layer of metal on top of a thin barrier layer before plating from solution can proceed. Therefore, a better understanding of how energetic Ar@super +@ and Cu@super +@ ions interact with copper surfaces is crucial for further development of both technologies. We present results of molecular dynamics (MD) simulations of Ar@super +@ and Cu@super +@ ions impacting model Cu surfaces with a variety of impact energies (50 - 200 eV) and angles. We modeled Cu-Cu interactions using the EAM potential energy function (PEF) and Ar-Cu interactions using the ZBL PEF.@footnote 1@ We report the distributions in reflected angles and energies for these ions. We report both total and differential sputter yields with respect to angle of ejection, and compare our MD results to recent experimental findings.@footnote 2@ The effect of changing ion energy and angle on these quantities is discussed. For example, we observe that the sputter yield for Ar@super +@ on Cu decreases as the Ar@super +@ ion's incident angle is increased from 30@super o@ to 60@super o@ from normal. These results shed light on the dynamics of low energy ion/metal surface interactions and provide a useful database of events for profile evolution simulations of Cu seed layer deposition and trench/via fill. @FootnoteText@ @footnote 1@ K. Gartner et al., Nucl. Instr. Meth. Phys. Res. B 102, p183 (1995). @footnote 2@ C. Doughty, S. M. Gorbatkin, and L. A. Berry, J. Appl. Phys. 82, p1868 (1997)

Plasma Science and Technology Division
Room 318/319/320 - Session PS-ThA

Diagnostics II
Moderator: G.L. Bell, Sematech

2:00pm **PS-ThA1 In Situ Surface Diagnostics in Plasma Processing: Present Status and Future Challenges**, ***E.S. Aydil,*** University of California, Santa Barbara **INVITED**

Understanding and controlling plasma-surface interactions in plasma etching and deposition is a prerequisite for achieving process goals. Towards that end, the last decade has witnessed a steady growth of research activity both in developing new plasma and in situ surface diagnostic methods and using them to address key problems in plasma processing.@footnote 1@ In this talk, we will review the recent progress in diagnostic methods with emphasis on in situ surface diagnostic techniques, their current limitations, and challenges for the next decade. Specifically, we will describe applications of techniques such as multiple internal reflection Fourier transform infrared spectroscopy,@footnote 2@ spectroscopic ellipsometry, and laser induced thermal desorption@footnote 3@ to problems in plasma etching and deposition. Simultaneous use of in situ surface diagnostics in conjunction with ex situ surface characterization methods such as X-Ray photoelectron spectroscopy and plasma gas phase diagnostic techniques such as optical emission spectroscopy has led to improved understanding of plasma etching and deposition processes. Examples from plasma etching of Si and SiO@sub 2@ and plasma deposition of hydrogenated amorphous silicon, fluorinated SiO@sub 2@ and silicon nitride will be reviewed. Despite the recent successes, major challenges remain both in advancing the capabilities of the existing surface diagnostics and applying the knowledge acquired to date to develop simple predictive models of surface processes. While some of the sophisticated surface diagnostic methods provide valuable information on surface reactions and species during process development, their use in manufacturing for real time process control is almost impossible due to their complexity. Inventing robust sensors and diagnostic tools for use in manufacturing remains a major challenge for the next decade. @FootnoteText@ @footnote 1@G. S. Oehrlein, Surf. Sci. 386, 222 (1997). @footnote 2@E. S. Aydil and R. A. Gottscho, Solid State Technol. 10, 181 (October 1997). @footnote 3@I. P. Herman, V. M. Donnelly, C. C. Cheng, K. V. Guinn, Jpn. J. Appl. Phys. 35, 2410 (1996).

2:40pm **PS-ThA3 Comparison of Surface Wave Plasma with ICP used in Oxide Etching**, *H. Kokura, S. Yoneda, K. Nakamura,* Nagoya University, Japan*; N. Matsumoto,* Sumitomo Metal In., Ltd., Japan*; M. Nakamura,* Fujitsu Ltd., Japan*;* ***H. Sugai,*** Nagoya University, Japan

High-density large-diameter SWP (surface wave plasma) is produced by microwave discharge at 2.45 GHz, without magnetic field. With application to SiO@sub 2@ etching in mind, comparison of SWP to ICP (inductively coupled plasma) at 13.56 MHz is made in such a way as to replace the antenna on the quartz plate from a slot type (SWP) to a single loop (ICP) in the identical plasma vessel where the discharge electron density, pumping speed and wall temperatures are kept at the same values. In order to set the electron density at the same value, a novel probe technique is developed, which enables reliable measurement of electron density even when the probe surface is contaminated by polymer deposition. First, impurity (CO@sub 2@, SiF@sub 2@) monitoring shows considerable sputtering of quartz window in case of ICP due to electrostatic antenna-plasma coupling. Second, a degree of dissociation of source gas (10% C@sub 4@F@sub 8@ + 90% Ar) at the same electron density is higher in ICP than in SWP. Third, the neutral radical densities (CF@sub 3@, CF, F) at the same electron density are ten times higher in SWP than in ICP. Fourth, as for the ionic composition, ICP contains CF@super +@ more than 90% while SWP has less CF@super +@ and more CF@sub 3@@super +@, C@sub 2@F@sub 4@@super +@ and C@sub 3@F@sub 5@@super +@. As a consequence, ICP is more highly dissociated than SWP at the same electron density. The origin of this difference is tentatively attributed to the high-energy electron population :optical emission spectroscopy of ArI line suggested 1.5 - 2 times more high-energy electron in ICP than SWP. The physical process leading to a difference in the electron energy distribution functions between ICP and SWP will be discussed, together with etching results. Finally, a radical composition of plasmas produced by an alternative etching gas, C@sub 3@HF@sub 7@O (HFE227), for environmental issue is measured in comparison to conventional gas C@sub 4@F@sub 8@.

3:00pm **PS-ThA4 An ICP Source Design with Improved Azimuthal Symmetry@footnote 1@**, ***M.H. Khater***[1], *L.J. Overzet,* University of Texas, Dallas*; B.E. Cherrington,* University of Dayton

The geometry of an inductively coupled plasma (ICP) source impacts the plasma and processing uniformity. A reasonably uniform source design does not always guarantee uniform plasma, however, because transmission line effects also impact its performance.@footnote 2@ These cause the current to vary along the coil length producing azimuthal asymmetries in the RF fields of planar sources, a non-uniform power deposition in the plasma and non-uniform processing rates. The azimuthal uniformity for planar coils can be improved somewhat but with significant drawbacks. A source geometry that is inherently uniform and is not adversely impacted by transmission line effects would be preferred. We will present what we think is just such an ICP source design. The geometry is three dimensional rather than planar and consists of two (or more) layers of full and semicircular loops with the RF current generally flowing in opposite directions. Typically, the "bottom" layer consists of full circular loops, while the "top" layer consists of semicircular loops. The length of the new source is greater than that of a similarly sized planar coil, nevertheless, both have inductances near 3 µH. We have measured the free space magnetic fields produced by one of these sources in the (r,@theta@) plane using a B-dot probe. It generated fields of higher azimuthal symmetry than the planar coil despite a larger current variation (I@sub out@/I@sub in@) along the source length. The average value of the peak azimuthal electric field for the new source was E@sub theta@/I@sub out@=0.24 V/(cm A) with a standard deviation of @sigma@=0.0085. The planar coil produced 0.32 V/(cm A) with @sigma@=0.027. The new source has been used to produce high density (10@super 11@-10@super 12@ cm@super -3@) Ar and SF@sub 6@ discharges at low pressures (5-20 mTorr) and to etch poly silicon. @FootnoteText@ @footnote 1@ This material is based upon work supported by Beta Squared Inc. under Grant No. UTD96-56 and by the State of Texas Advanced Research Program under Grant No. 009741-043. @footnote 2@ M. Kushner, et al., J. Appl. Phys. 80, 1337 (1996).

3:20pm **PS-ThA5 Characterization of 100 MHz Inductively Coupled Plasma (ICP) by Comparison with 13.56 MHz ICP**, ***H. Nakagawa,*** *S. Morishita, S. Noda, M. Okigawa, M. Inoue, M. Sekine,* Association of Super-Advanced Electronics Technologies (ASET), Japan

The effect of the excitation frequency on gas dissociation was investigated using a multi-spiral coil in inductively coupled plasma (ICP). The same apparatus except for wave generators and matching circuits was used in the 100 MHz@footnote 1@ and 13.56 MHz excitation wavelength experiments. The electron density (Ne) and electron temperature (Te) in the Ar plasma were measured using a Langmuir probe. In both cases, the value of the Ne was around 2 e+11 cm@super -3@ at the excitation power of 2 kW in 3 Pa (Ar = 400 sccm). Although the Ne in 13.56 MHz plasma is a little higher than that in the 100 MHz plasma, Te (~3) in the 13.56 MHz plasma is higher than that (~2) in the 100 MHz plasma. From the dependence of the radial distribution of the Ne on the ICP source power, it was found that the 13.56 MHz-ICP was produced in a space under the coil area, and that the 100 MHz-ICP was generated throughout the reactor. This is because of the strong capacitive coupling in the 13.56 MHz-ICP, and because the inductive coupling in the 100 MHz-ICP is stronger than that in the 13.56 MHz-ICP. In the C@sub 4@F@sub 8@ / Ar plasma, CF@sub X@ (x=1, 2, 3) radical densities in the reactor wall were measured by appearance mass spectrometry (AMS),@footnote 2@ and the F radical density was evaluated using actinometry through optical emission spectroscopy of Ar (750.4 nm) and F (703.7 nm).@footnote 3@ The degree of dissociation of C@sub 4@F@sub 8@ in the 100 MHz-ICP was higher than that in the 13.56 MHz-ICP, but the CF@sub 2@ / F density ratio in the 100 MHz-ICP was 3 ~ 5 times as large as that in the 13.56 MHz-ICP. This result indicates that the dissociation of a high order (ex. CF@sub 2@ + e --> CF + F + e) in the 13.56 MHz-ICP is larger than that in the 100 MHz-ICP. Thus, it was demonstrated that the 100 MHz-ICP has a greater ability to suppress F radical generation than the 13.56 MHz-ICP. @FootnoteText@ This work was supported by NEDO. @footnote 1@H. Nakagawa et al.: Proc. 14th Symp. on Plasma Processing,136 (Hamamatsu, 1998). @footnote 2@M. Goto et al.: Jpn. J. Appl. Phys. 33 (1994) 3602. @footnote 3@J. S. Jenq et al.: Plasma Source Sci. Technol. 3 (1994) 154.

[1] **PSTD Coburn-Winters Student Award Finalist**

3:40pm **PS-ThA6 Multi-Frequency Operation of RIE and ICP Sources@footnote 1@**, ***S. Rauf***, *M.J. Kushner,* University of Illinois, Urbana-Champaign

In both inductively and capacitively coupled rf discharges, the source frequency strongly influences the plasma and electrical properties. Multiple sources at different frequencies are often simultaneously used to combine their attractive features. For example, the goal of dual-frequency RIE plasmas is to separately optimize the magnitude and energy of ion fluxes to the substrate. If the source frequencies are significantly different from each other, the resulting plasma properties can generally be characterized in terms of the separate contributions of the individual sources. However, when the frequencies are close to each other (e.g., 6.78 MHz and 13.56 MHz), the sources interact through the nonlinear plasma medium, thereby complicating this additive relationship. The dynamics of rf plasma processing reactors with multi-frequency sources have been investigated using a coupled plasma equipment-circuit model. In capacitively coupled Ar and Ar/CF@sub 4@ discharges, the addition of a high frequency source (27.12 MHz) on the opposing electrode decreases the magnitude of the dc bias at the substrate (13.56 MHz) due to nonlinear interaction between the separately powered sheaths and a reapportionment of current. In ICP reactors, the dc bias on the substrate has a strong dependence on the rf bias frequency (becoming more negative at higher frequencies) due to the differences in sheath impedance at the powered substrate and the grounded walls. This relationship can be altered by repositioning the antenna which, in turn, reapportions the current collected on biased and grounded surfaces. It was also found that by adding rf sources at remote locations from the substrate in ICP reactors, such as small areas of the wall, one can control the dc bias at the substrate without appreciably changing the ion flux or electron temperature. @FootnoteText@ @footnote 1@Work supported by AFOSR/DARPA, SRC and NSF.

4:00pm **PS-ThA7 Diagnostics in a Novel Capacitively Shielded, Inductively Coupled Plasma Source**, ***V.A. Shamamian***, *J.E. Butler, D. Leonhardt,* Naval Research Laboratory; *J.L. Giuliani,* Naval Research Laboratory, US

An electrostatic shield in the form of a slotted metal cylinder is often placed between the exciting coil and the dielectric discharge tube of an inductively coupled plasma system in order to screen the electric field generated by the coil. Such fields can, under some circumstances, have a deleterious effect on the process for which the plasma is being used. For very high power systems, the dielectric discharge tube can be replaced by a thick-walled, water-cooled, slotted metal cylinder (i.e., a cold crucible). It is not generally realized that the electrostatic shield can also lead to a significant reduction of the r.f. magnetic fields inside the tube as well as altering its axial distribution. This effect needs to be considered in detailed modeling of inductively coupled plasma systems and is of practical importance in determining the impedance the plasma presents to the r.f. generator. In this combined experimental and theoretical work, we have employed induction probes to study the effect by measuring the r.f. magnetic field inside hydrogen discharges. We interrogated the level to which the plasma screens the field as a function of pressure and coupled power. In addition, we have employed optical emission imaging techniques and a radiation transport model to extract the axial and radial dependence of the electron and neutral temperatures, and plasma spatial extent in the axial direction. We have found that the electron temperature is constant in the axial direction but strongly dependent in the radial dimension, and the plasma extent is self-similar with respect to the value of power divided by pressure. Finally, we have developed electromagnetic models that give good agreement with the plasma induction probe observations. We are currently developing a global 2D model which incorporates electromagnetics, gas phase chemistry and transport, and surface recombination. Work supported by IST/BMDO, DARPA, and ONR.

4:20pm **PS-ThA8 Volume/Surface Effects on Dissociation Processes in Ar/C@sub 4@F@sub 8@ Plasma**, ***K. Kinoshita***, Association of Super-Advanced Electronics Technologies (ASET), Japan; *S. Morishita, S. Noda, M. Okigawa, M. Inoue, M. Sekine,* ASET, Japan

We clarified that the control of multistage dissociation in Ar diluted C@sub 4@F@sub 8@ plasma via the total number of collisions, @tau@ N@sub e@ <@sigma@v>,@footnote 1@ is essential in establishing a high-performance SiO@sub 2@ etch process in a narrow-gap parallel plate reactor. For the scaling of the reactor to a larger wafer size in the near future, a wider gap space will be required to assure uniformity of the gas supply and exhaust. Changing the gap space (i.e, volume/surface ratio) must affect the gas dissociation process by changing total number of collisions. Here, @tau@ and N@sub e@ can be controlled by the pumping speed and source power. Therefore, we examined the change in <@sigma@v> on the gap space and its effect on the dissociation process. Two kinds of UHF (500 MHz) plasma sources were used. One source had a spoke antenna coupled with plasma through a quartz top plate and the other had a carbon top plate antenna with a magnetic field of ECR condition. In both systems, when the gap space was widened, the N@sub e@ increased and <@sigma@v> for the C@sub 4@F@sub 8@ dissociation decreased, when @tau@ was constant. <@sigma@v> for excitation for ArI emission also decreased with increasing gap space. Kinetic analysis through rate equations indicated that the reaction rate constant <@sigma@v> for the F generation reaction decreased with increase in gap space in both plasma sources. These results suggest that changing the electron energy distribution by changing the gap space significantly influences the reaction rate constant of the dissociation reactions in the Ar/C@sub 4@F@sub 8@ plasma. @FootnoteText@ This work was supported by NEDO. @footnote 1@ T. Tatsumi et al., Jpn. J. Appl. Phys., 37 (1998) to be published

4:40pm **PS-ThA9 Investigation of the Gasphase of Expanding Ar/C@sub x@H@sub y@ Plasmas**, *A. de Graaf, M.F.A.M. van Hest,* ***K.G.Y. Letourneur***, *M.C.M. van de Sanden, D.C. Schram,* Eindhoven University of Technology, The Netherlands

An expanding argon plasma into which several C@sub x@H@sub y@ precursors are injected was used for the deposition of diamond-like carbon films. The argon plasma is created in a cascaded arc and expands into a low-pressure vessel, where precursor gases, such as CH@sub 4@, C@sub 2@H@sub 2@, C@sub 2@H@sub 4@ and C@sub 2@H@sub 6@ are injected into the beam. The gasphase of these plasmas was investigated by means of Fourier Transform Infrared (FTIR) absorption spectroscopy and Mass Spectrometry (MS). The consumption of the different precursor gases was derived from both FTIR and MS measurements for several arc currents, pressures and flows. The results from the two techniques are compared in order to eliminate the effect of temperature and to distinguish whether reaction products are formed in the background or in the plasma beam. By correlating the depletion measurements with the growth rate measured in situ by ellipsometry, information is obtained on the reactions taking place inside the plasma and during deposition. Assuming that only argon ions are contributing to the dissociation of the C@sub x@H@sub y@, the electron energy being too low (typically 0.2 eV in these plasmas), the ionization degree of the arc can be deduced as function of arc current and argon flow. The measurements also prove that other stable monomers are produced in the plasma phase, i.e. polymerization is taking place. The possible polymerization reactions, occurring either in the gasphase or at the reactor walls, will be discussed for the different precursor gases.

5:00pm **PS-ThA10 Electrical Control of Spatial Uniformity of Chamber-Cleaning Plasmas Investigated using Planar Laser-Induced Fluorescence**, ***K.L. Steffens***, *M.A. Sobolewski,* National Institute of Standards and Technology

Fluorocarbon plasmas are widely used by the semiconductor industry for in situ cleaning of PECVD chambers. Control and optimization of chamber-cleaning processes are critical for reduction of both the emission of greenhouse gases and chamber-cleaning time. Also the spatial distribution of chemically reactive species in the plasma should be tailored to maximize the cleaning rate at appropriate surfaces. Previous studies in parallel-plate reactors have indicated that reactive species density distributions, plasma emission, and cleaning rates are correlated to the rf current measured at the upper, grounded electrode. In this study, the current at the upper electrode was varied by adjusting the impedance between the upper electrode and ground, and the resulting changes in plasma uniformity were investigated using optical techniques. Measurements were made in O@sub 2@/CF@sub 4@ and O@sub 2@/C@sub 2@F@sub 6@ plasmas in the capacitively-coupled Gaseous Electronics Conference Reference Cell at pressures from 0.1 to 1 Torr. The 2-dimensional density distribution of the reactive radical, CF@sub 2@, was measured using planar laser-induced fluorescence (PLIF), and the regions where reactive species were generated were determined using spatially-resolved, broadband optical emission. As the current at the upper electrode was varied, changes were observed in the axial symmetry of the broadband emission and in the radial uniformity of the CF@sub 2@ PLIF. These results suggest that electrical control of the current paths through the plasma could be used to control the spatial distribution of reactive chemical species, aiding in the optimization of chamber-cleaning plasmas and other fluorocarbon plasmas.

Plasma Science and Technology Division
Room Hall A - Session PS-ThP

Plasma Science and Technology Division Poster Session

PS-ThP1 Improvement on Lithography Pattern Profile by Plasma Treatment, ***C.P. Soo,*** National University of Singapore, Singapore*; M.H. Fan,* Chartered Semiconductor Manufacturing Ltd., Singapore*; A.J. Bourdillon,* National University of Singapore, Singapore*; L.H. Chan,* Chartered Semiconductor Manufacturing Ltd, Singapore, Republic of Singapore

Chemically amplified (CA) resist is designed to have high sensitivity towards KrF excimer laser stepper. Unavoidably, this brings about substrate-specific effect as well. A few years recently, there are publications reported that during investigation of resist pattern profile by cross-sectional SEM micrographs, positive CA resist on nitride wafers revealed ?footing?.@footnote 1@ Various kinds of postulation had been made for degradation of resist pattern profile at resist/substrate interface by substrate poisoning. Sturtevant et al.@footnote 2@ reported that the chemical contaminants of substrate degraded the resist patterns on nitride and other substrate. A. Usujima et al.@footnote 1@ reported that substrate treatment using oxygen plasma is extremely effective in improvement on resist footing problem. However, down-stream oxygen plasma treatment needed to be optimized as excessive plasma treatment gave adverse performance because of surface damage. In this study, further optimization on oxygen plasma treatment was done. Besides using oxygen plasma, N@sub 2@O plasma treatment, was experimented to obtain repeatable straight resist profile. Besides , the substrate-specific effect was discussed from the standpoint of chemical interference from nitride substrate. The contaminants on the nitride substrate was studied by XPS and GC mass-spectrometry. XPS and GC mass-spectrometry were also used to investigate the effect of various surface treatments. The performance of each kind of surface treatment was evaluated by looking at cross-sectional profiles. @FootnoteText@ @footnote 1@ A. Usujima, K. Tago, A. Oikawa, K. Nakagawa, "Effects of substrate treatment in positive chemically-amplified resist", Proc. SPIE, vol 2438, pp529-39, 1995 @footnote 2@ J. Sturtevant, S. Holmes, S. Knight, D. Poley, P. Rabidoux, L. Somerville, T. McDevitt, E. Valentine, W. Conley, A. Katnani, J. Fahey, "Substrate contamination effects in the processing of chemically amplified DUV photoresists", Proc. SPIE, vol 2197, pp770, 1994.

PS-ThP2 Tantalum Film for X-ray Lithography Mask Deposited by Electron Cyclotron Resonance Plasma Source Coupled with Divided Microwaves, ***H. Nishimura,*** *T. Ono, M. Oda, S. Matsuo,* NTT System Electronics Laboratories, Japan

An advanced ECR plasma source by which a conductive film can be stably formed has been developed and applied to Ta film formation.@footnote 1@ We investigate the applicability of ECR-Ta as absorbers of x-ray masks. It is found from TEM observation that an ECR-Ta film is a polycrystal film that has a large grain size of (>0.5 μm) and a dense microstructure. The x-ray absorber material must satisfy several conditions, such as low, uniform, and stable stress. The stress change of ECR-Ta film is rarely observed not only in the air but also under the SR irradiation condition. In order to control film stress, we have investigated the stress-depth distribution. The stress is analyzed to be a sum of an interfacial stress (retained near the film-substrate interface) and a bulk stress (retained in the film bulk). These individual stresses can be independently controlled. The interfacial stress depends on the substrate temperature, working-gas pressure, and deposition rate. The bulk stress varies toward compressive by adding Ar to the sputtering gas (Xe). A low stress film with no stress-depth distribution (15 MPa at 200-400 nm) is obtained by optimizing deposition parameters. A highly accurate x ray mask is achieved by using an ECR-Ta film. These results show that the dense microstructure including the grain boundary rather than the film structure (polycrystal or amorphous) is important for a highly accurate x-ray mask. The ECR sputter method is suitable for depositing dense microstructure film because of the enhancement of film formation reaction on the surface by low energy (10-30 eV) ion irradiation. @FootnoteText@ @footnote 1@ H. Nishimura, et al., J. Vac. Sci. Technol. A15 (19 97) 707.

PS-ThP3 Control of Ion Energy Distribution at Substrates During Plasma Processing, ***S.B. Wang,*** *A.E. Wendt,* University of Wisconsin, Madison

It is well-known that ion bombardment of the substrate is one factor that makes plasma processing indispensable in semiconductor fabrication. In an effort to understanding the factors governing selectivity in oxide etch processes, we examine the energy of ion bombarding the substrate. We start with a design study for an experimental system producing a narrow distribution of ion energies at the substrate. With fine control over the energy of the nearly monoenergetic ions, we can elucidate the effect of ion energy on selectivity. The ion energy distribution reaching the substrate has been investigated by a self-consistent spherical shell plasma model. The results show that the broadening of ion energy distribution depends on the area ratio of substrate to grounded wall which is varied by changing the radii of the two spherical shell electrodes. As the area ratio increases, the plasma potential is more strongly modulated by the rf potential on the powered electrode. Therefore, the ion energy, which is proportional to the difference between plasma potential and substrate potential, becomes narrower with increasing area ratio. This result suggests differences in processing performance between tools with similar plasma conditions but different effective grounded wall areas, such as ECR and inductively coupled plasmas. In addition, we show that the ion energy distribution can be controlled by modulation of the voltage waveform applied to the substrate electrode. In the simulation, the broadening shrinks as low as ~2T@sub e@(T@sub e@ is electron temperature in Volts) as compared to 20T@sub e@ or greater for a sinusoidal voltage waveform. In addition, the shape of the energy distribution is single peak rather than a saddle. This is a good tool for threshold energy studies. Based on these results, we have designed a system for experimental study of ion energy thresholds for selective etching. Experiments in ion energy control and selectivity improvement in experiment are currently underway. This work supported by NSF Grant #EEC8721545

PS-ThP4 Simulations of Electronegative Discharge Sheaths@footnote 1@, ***S.K. Kanakasabapathy,*** *J.L. Kleber, L.J. Overzet,* University of Texas, Dallas

Measuring negative ion concentrations in discharges continues to be difficult. Negative ions do not easily escape the glow center and as a consequence are more difficult to probe than electrons or positive ions. When the negative ion concentration becomes a large enough fraction of the total negative charge, however, the plasma kinetics can become dominated by the ions, and the electrons can become relatively insignificant. This kind of plasma is sometimes referred to as an "ion-ion plasma." We have developed a one-dimensional, time dependent, fluid model (SHEATHSIM) to simulate the behavior of ions and electrons near RF biased electrodes, double probes and a novel four point probe in just such electronegative plasmas. In each sheath, the ion momentum conservation and continuity equations, closed by Poisson's equation are solved for a given set of bulk densities, temperatures and mean free path lengths. The set of equations for two such sheaths are closed by a common bulk potential and current continuity. Such modeling helps us to understand the measurements we are making of highly electronegative "ion-ion" discharges. In this poster, we will present the results from our simulation as compared to measurements made in SF@sub 6@ and Cl@sub 2@ discharges. @FootnoteText@ @footnote 1@ This material is based upon work supported by the National Science Foundation under Grant No. CTS-9713262 and by the State of Texas Advanced Research Program under Grant No. 009741-043.

PS-ThP5 Negative Ions in Inductively Coupled Plasmas@footnote 1@, ***J.L. Kleber,*** *L.J. Overzet,* University of Texas, Dallas

The effects of negative ions on continuous wave and pulsed low pressure inductively coupled plasmas (ICP's) are being investigated using a Langmuir probe and a microwave interferometer. The sheath resistance (R@sub sh@) can cause the plasma potential to rise when a Langmuir probe in the plasma is biased above floating potential.@footnote 2@ This can lead to errors in calculating plasma parameters such as electron density (n@sub e@), electron temperature, and the electron energy probability function (EEPF). We have measured R@sub sh@ for continuous wave ICP's in the Gaseous Electronics Conference (GEC) reactor in argon and nitrogen and will measure it in a mixture of argon and chlorine all at or under 50 mTorr. We found that R@sub sh@ had a power law dependence on n@sub e@ and will demonstrate how this arises. We have also investigated the spatial and temporal behavior of plasma parameters in pulsed pure argon ICP's and will investigate them in a mixture of argon and chlorine. We focus on the afterglow when it is possible for the negative ions to influence more the chemistry of the plasma as the electron density decays. @FootnoteText@ @footnote 1@This material is based upon work supported by a National Science Foundation under a Graduate Research Fellowship and Grant No. CTS-9713262 and by the State of Texas Advanced Research Program under Grant No. 009741-043. @footnote 2@M. B. Hopkins, J. Res. NIST 100, 415-425 (1995)

PS-ThP6 Time Resolved Electrostatic Probe Measurements of Electron Temperature and Plasma Density Radial Profiles in a Pulsed ICP Plasma, ***X.M. Tang**, D.M. Manos,* College of William and Mary

This paper reports results of a study of a pulsed 13.6 MHz ICP plasma which has been configured for multiple purposes, including etch, cleaning, and deposition. The pulse-packet frequency can be varied over a wide range. For these studies it was varied from 50Hz to 10kHz to create plasmas in a variety of gas mixtures including oxygen, carbon tetrafluoride, and argon. The plasma is characterized using a variety of methods, including electrostatic probes and optical emission. Probe data were analyzed using nonlinear regression methods and equivalent resistance methods. The comparative advantages of each will be discussed. The agreement between the methods is good. Spatially resolved measurements of the time-dependent electron density and temperature, taken on the time scale of the power modulation, are presented as a function of rf power, frequency, duty cycle, and gas composition. These results confirm, among other things, that the modulated plasma density is higher than the plasma density resulting from CW operation at the same average power. High-temperature transients at the pulse onset do not appear at high frequencies. Comparisons with similar prior studies and with simulated plasma models will also be presented.

PS-ThP7 Electron and Negative Ion Density in BCl@sub 3@ / Cl@sub 2@ / Ar Gas Mixtures, ***G.A. Hebner**, M.G. Blain,* Sandia National Laboratories*; T.W. Hamilton,* Sandia National Laboratories, U. S. A*; C.A. Nichols, R.L. Jarecki,* Sandia National Laboratories

Electron and negative ion density have been measured in a modified Applied Materials DPS chamber using gas mixtures of BCl@sub 3@, Cl@sub 2@ and Ar. Measurements were performed for four different substrate types to examine the influence of surface material on the bulk plasma properties; aluminum, alumina, photoresist and Aluminum / PR. The plasma conditions of source power, bias power, pressure, Cl@sub 2@ / BCl@sub 3@ ratio, total flow rate and argon addition were varied over a wide operational parameter space. Electron densities in the Cl@sub 2@ / BCl@sub 3@ mixtures varied between 0.5 and 8.0 x 10@super 12@ cm@super -2@ or approximately 0.25 to 4 x 10@super 11@ cm@super -3@. Photodetachment measurements of the negative ion density indicate that the negative ion density is smaller than the electron density. In general, we noted that photoresist had a major influence on the electron and negative ion density. In most cases, the electron density above wafers with PR was a factor of two lower while the negative ion density was a factor of two higher than the aluminum or alumina surfaces. The trends observed in the DPS chamber were similar to trends observed in the previous measurements in the GEC rf reference cells at Sandia. The only exception was the pressure dependence of the electron and negative ion density. This difference in the two systems is likely related to the different coil configuration and geometry of the two chambers. This work was performed at Sandia National Laboratories and supported by SEMATECH, Applied Materials, and the United States Department of Energy (DE-AC04-94AL85000).

PS-ThP8 Rare Gas Dilution of Fluorocarbon Plasmas: Te Measurements using TRG-OES and Processing Implications, ***H.L. Maynard**,* Bell Laboratories, Lucent Technologies*; M.V. Malyshev,* Bell Laboratories (Also at Princeton University)*; W.W. Tai, V.M. Donnelly,* Bell Laboratories, Lucent Technologies

In the etching of sub-250 nm oxide contacts and vias with high-densityplasmas, rare gas dilution of the fluorocarbon etchant gas has several benefits, including the suppression of etch stop. The addition of a small amount of Ar to a C@sub 2@F@sub 6@ plasma in an Applied Materials' High Density Plasma etcher increases the oxide etching rate (as measured in features > 350 nm). Further addition of Ar does not decrease the oxide etching rate until the diluent concentration exceeds ~80%. For Ar dilution between 20-80%, sufficient fluoropolymer deposits on the oxide surface to provide reactant, and the energy required to drive the etching reaction can apparently be provided equally well by either an Ar or a CF@sub x@ ion. For [Ar] > 80%, insufficient fluoropolymer is deposited to provide sufficient reactant for the oxide etching or to protect the photoresist. For relatively dilute mixtures (50 < [Ar]

PS-ThP9 Molecular Dynamics Simulation of Cu and Ar Ion Sputtering of Cu Surfaces@footnote 1@, ***J.D. Kress**, D.E. Hanson, A.F. Voter,* Los Alamos National Laboratory*; C.-L. Liu, D.G. Coronell,* Motorola

In ionized physical vapor deposition (PVD) used in Cu interconnect technology, the interaction of energetic ions with the growing Cu substrate is not well characterized by a constant sticking probability independent of ion impact angle or energy. Such detailed information, not known experimentally, is necessary input for realistic feature scale modeling of step coverage in the metallization of vias and trenches in integrated circuits. Here we describe the results of molecular dynamics (MD) simulations of sputtering of Cu (111) and (100) surfaces by Cu and Ar ions suitable for incorporation into feature scale simulations. For the interatomic potentials, the many-body embedded atom method for Cu-Cu and a Ziegler-Biersack-Littmark pair potential for Ar-Cu were used. For each impact angle and energy (10 to 100 eV for Cu ion and 50 to 175 eV for Ar ion), a series of 150 impact events were run with an initial surface temperature of 300 K. At the end of each series, the average sputter yield (number of Cu atoms sputtered per impact), sticking probability, reflection angle and energy, and sputtered angle and energy were calculated as a function of impact energy and angle. For Cu and Ar ion impact energies below 50 eV or angles of incidence of 70 degrees or greater, the sputter yield is essentially zero. For Cu ion impact angles of 20 degrees or less, the sticking probability is essentially unity for all impact energies studied. @FootnoteText@ @footnote 1@Supported in part by US Department of Energy Cooperative Research and Development Agreements (CRADAs).

PS-ThP10 Monte-Carlo Simulation of Atomic Scale InP Surface Etching, *L. Houlet,* ***A. Rhallabi**, G. Turban,* Institut des Materiaux de Nantes, France

Monte-Carlo method has been applied to simulate CH@sub 4@-H@sub 2@ Reactive Ion Etching (RIE) process for an atomic scale InP Surface. Two neutral precursor types and one ion type have been considered in the surface etching process.CH@sub 3@ and H adsorbed precursors are assumed to be bonded to the surface substrate leading to the desorption of the indium and phosphorous sites respectively, while the energetic ions allow the sputtering of the In(CH@sub 3@)@sub x@ and P(H)@sub x@ (0@<=@x@<=@3). XPS analyses show that the ion bombardment gives rise to an amorphous surface. Consequently, the initial InP material was represented by the stoichiometric indium and hydrogen sites which were randomly placed in the 3D discrete network. The model takes account of precursor and site identities, ion preferential sputtering, isotropic transport of neutrals to the surface, adsorption, migration, reaction or desorption of neutrals as well as the independent choice of binding energies between each neutral and site type. The surface migration process is based on the empirical bond-breaking model which is used to determine the amount of energy which must be supplied for a physisorbed precursor to move from one site to another. This process depends on the substrate temperature and the bonded energies for each site type. By setting the available experimental data, the simulation results confirm the surface phosphorous depletion which was observed by XPS analyses. The increase in RMS roughness, the etching rate and neutral surface coverage is obtained when the atomic hydrogen ion flux ratio increases.

PS-ThP11 Analysis of Fast Neutrals in Plasma Monitoring, ***J. Wei**, R.E. Pedder,* ABB Extrel

Fast neutrals are generated in plasma and high energy ion sputtering processes. The kinetic energy of the fast moving molecules can be as high as a few hundred electron volts. The analysis of these fast neutrals with a regular residual gas analyzer has been shown to be very difficult in many cases. The first problem in the analysis is the decrease in the number of ions from the ionizer as the kinetic energy of the fast neutrals increases. The second problem is the loss of ion transmission through the quadrupole mass filter with the high energy ions from the fast neutrals. The combination of these problems often translates into distorted peak shapes in the mass spectrum and very low sensitivity for the fast neutrals. We will present the results on the analysis of fast moving neutrals with a quadrupole mass spectrometer. This quadrupole mass spectrometer is equipped with a biasable quadrupole mass filter assembly and an ion energy analyzer. With this setup, we can either slow down all the ions through a bias potential on the mass filter assembly or select only the ions at a given kinetic energy range and then slow them down to an optimum kinetic energy when they travel into the quadrupole mass filter. This bias potential on the quadrupole mass filter assembly minimizes the ion transmission loss through the quadrupole and restores the sensitivity for the detection of the fast neutrals. Furthermore, when the kinetic energy of the fast neutrals are a couple of electron volts or higher, we can use the energy analyzer to distinguish the fast neutrals from the same gas components or components with identical mass in the residual gas background.

PS-ThP12 The Application of Helicon Antennas as a Secondary Plasma Source for Ionized PVD, ***D.B. Hayden***, *D.N. Ruzic, D.R. Juliano, M.M.C. Allain,* University of Illinois, Urbana

Ionized PVD may extend the usefulness of PVD for several generations by allowing the directional fill of higher aspect-ratio features. Previous work typically has used an inductively coupled plasma (ICP) coil of various designs to drive a high-density plasma in between the sputter target and substrate. A different approach using a helicon antenna to drive the high-density plasma instead is discussed. Helicon-produced plasmas are renowned for their high coupling efficiency given modest input powers. This remotely located source (external to the sputter chamber) has distinct advantages over an immersed ICP coil by eliminating shadowing and flaking problems. Helicon plasmas also have higher maximum achievable densities, thus yielding a higher ionization fraction than ICP coil-driven plasmas. Data for one external source (with various antennas including the helical and Nagoya type III) are shown. The surrounding electromagnets needed for igniting and sustaining the helicon plasma are variable up to 1.5 kG. Pressures investigated are 5-50 mTorr. The effects of multiple antennas surrounding the chamber, which would improve uniformity and density considerably, are discussed.

PS-ThP13 CF@sub 2@, CF Radical Behaviors in a Magnetized Inductively Coupled Plasma and the Correlation with Oxide Etch Characteristics, ***J.H. Kim***, *H.J. Lee, K.W. Whang,* Seoul National University, South Korea*; J.H. Joo,* Kunsan National University, South Korea

Fluorine-based plasma has been used to etch SiO@sub 2@ layer in LSI circuit fabrications, and the low-pressure high-density plasma sources are being studied for ultra-fine structure fabrication. It has been known that the high density plasma has low etch selectivity over Si, but recent studies show that the highly selective SiO@sub 2@ etching is possible in the restricted area. However, the etching mechanism was not revealed clearly until now. A key parameter governing the selectivity is believed to be the ratio of (CF@sub x@) density to fluorine atom density and of radical density to ion density. Here, we report the CF@sub 2@ and CF radical behaviors based on appearance mass spectrometry(AMS), actinometry and laser induced fluorescence(LIF), along with the correlation between other species and the etch characteristics in the magnetized inductively coupled plasma which was reported for the highly selective SiO@sub 2@ etching. A 13.56MHz RF power up to 2.5kW was coupled to the 4 turn antenna and generated a CF@sub 4@ or C@sub 4@F@sub 8@ plasma at the operating pressure of 1-10mTorr. The CF@sub 2@ radical increased with the operating pressure and decreased with the main RF power, which were well coincident with the global model simulation. But the rates of increase were somewhat different according to the diagnostics tools. The increase rate measured with AMS was about 1.5 times greater than those measured with LIF or actinometry. This was caused by the plasma perturbation in using the AMS technique, the quartz contamination while LIF or actinometry and so on. We will discuss the CF@sub 2@ and CF radical behaviors with the various plasma process parameters and their correlation between other species and etch characteristics. Especially, we will present the effect of bias power on the plasma chemistry near the substrate.

PS-ThP14 Determination of Gas Phase Species Concentrations in High Density Plasmas for Dielectric Deposition, ***M.L. Jezl***, *R.C. Woods,* University of Wisconsin, Madison

Simultaneous application of various gas-phase spectroscopic techniques are used in order to determine the species present in a 2.45 GHz electron cyclotron resonance (ECR) reactor. The plasmas investigated are primarily silicon dioxide and fluorinated silicon dioxide deposition plasmas (SiH@sub 4@/SiF@sub 4@/TEOS + O@sub 2@). For these plasmas we are able to determine absolute concentrations of many of the important species present, while relative concentrations can be determined for many more. Among the techniques utilized are microwave spectroscopy (which can detect species densities as low as 10@super 9@ cm@super -3@), Fourier transform infrared (FTIR) spectroscopy, and silicon atomic absorption spectroscopy. Microwave and FTIR spectroscopy have demonstrated their ability to detect highly complimentary subsets of detectable molecular species. This has greatly expanded the range of species that can be monitored concurrently. In addition to determining absolute and relative concentrations of gas-phase species, we attempt to correlate the observed trends of their concentrations with the resulting film properties such as thickness, refractive index, infrared absorption, and wet etch rate. Molecules monitored include CO, CO@sub 2@, H@sub 2@O, HF, SiH@sub 4@, SiF@sub 4@, SiF@sub 2@, TEOS, H@sub2@CO, C@sub 2@H@sub 5@OH, and other TEOS decomposition products. @FootnoteText@ This work was supported by the NSF under Grant no. EEC-8721545.

PS-ThP15 Characterization of the Reactive Species in a Helium/Oxygen Atmospheric-Pressure Plasma Jet, ***J.Y. Jeong***, *S.E. Babayan, A. Schuetze,* University of California, Los Angeles*; J. Park, I. Henins,* Los Alamos National Laboratory*; R.F. Hicks,* University of California, Los Angeles*; G.S. Selwyn,* Los Alamos National Laboratory

An atmospheric-pressure plasma jet has been developed. The jet etches organic polymer films with an He/O@sub 2@ gas feed. In addition, silicon, silicon dioxide, and metal films have been etched with an He/CF@sub 4@/O@sub 2@ gas mixture. The reactive species in the plasma jet effluent and their chemistry have been investigated by optical and infrared emission spectroscopy, chemical titration, and numerical modeling. An ozone density of 10@super 14@-10@super 16@ was measured by UV absorption and the oxygen atom concentration is believed to be of same order of magnitude. The charged particle flux, monitored with a Langmuir probe, has been found to be around 10@super 14@ cm@super -2@ s@super -1@ in the effluent. With regard to kapton etching, it appears that oxygen atoms and possibly metastable oxygen molecules are the key reactive intermediates in this process. At the meeting, the chemistry of the plasma jet will be compared to conventional low-pressure plasma discharges.

Plasma Science and Technology Division
Room 318/319/320 - Session PS-FrM

Plasma-Surface Interactions - II

Moderator: J.E. Johannes, Sandia National Laboratories

8:20am **PS-FrM1 Large Enhancement of Silicon Etch Rate by Metal Contamination**, ***P.G.M. Sebel*** [1] , *L.J.F. Hermans, H.C.W. Beijerinck,* Eindhoven University of Technology, The Netherlands

Given the ever decreasing dimensions of I.C.'s, it is essential to understand the various influences which affect the etching behaviour. We found a remarkably large enhancement of silicon etch rates by even small contamination with Ni and W. Our experiments indicate that the contamination migrates into the silicon due to vacancy production by ions. The experiments were performed in a molecular beam setup, where silicon is etched by XeF@sub 2@ and Ar@super +@ ions. The etch behaviour is monitored by a mass spectrometer using the SiF@sub 4@ signal. The effect of contamination appears very pronounced when the ion beam is switched off. With contamination, a temporary enhancement of the spontaneous etch rate is measured. With traces of contamination in the order of 0.01 ML the etch rate may be enhanced by a factor of 2 for W and somewhat less for Ni. It is concluded that the contamination moves into the silicon by diffusion to vacancies created by the Ar@super +@ ions, as proposed by Hart et. al. for Cu contamination.@footnote 1@ For 1 keV Ar@super +@ ions the contamination moves to a depth of 30 Å, equal to the penetration depth of the ions. As the effect of contamination disappears after etching of 170 Å, it is concluded that contamination has a catalytic effect on the silicon etch rate. Simulations, which describe the measured effect of contamination very well, indicate that only 3% of the contamination is removed after etching a monolayer silicon. Besides this catalytic effect, there are indications that the etch rate can be lowered under certain conditions, because of the formation of silicides. @FootnoteText@ @footnote 1@R.R. Hart, H.L. Dunlap and O.J. Marsh, J. Appl. Phys. 46, 1947 (1975).

8:40am **PS-FrM2 Laser Detection of Chlorinated Neutral Etch Products During Cl@sub 2@ / Ar@super +@ Etching of Si(100)**, ***N. Materer,*** *R.S. Goodman, S.R. Leone,* JILA, NIST, and University of Colorado, Boulder

Pulsed laser single-photon ionization time-of-flight mass spectrometry is used to investigate neutral etch products formed during ion enhanced etching of Si(100). Single-photon ionization is accomplished using the ninth harmonic of a Nd:YAG laser at 118 nm to ionize neutral species. This approach eliminates dissociative ionization difficulties found in conventional electron impact ionization. Ions are first ejected from the region in frunt of the wafer by pulse field extraction prior to the laser pulse. The Ar@super +@ ion bombardment energy is varied from 275 to 1000 eV, and the flux of molecular chlorine is varied from 10@super 1@@super 4@ to 10@super 1@@super 5@ molecules per cm@super 2@. Under all conditions examined, SiCl is the major product. Neutral Si atoms are also detected during etching and there is some evidence for SiCl@sub 2@. The Si and SiCl products decay within 20µsec after a 500µsec ion pulse. This fast decay supports a mechanism in which these etch products are formed in a direct collisional process. In addition, the influence of the molecular chlorine flux is examined in detail. The introduction of molecular chlorine is found to first rapidly increase the yield of neutral Si and, at higher fluxes, to slowly decrease the yield. This subsequent decrease is attributed to the generation of an increasingly chlorinated surface. As in the case of Si, the yield of SiCl as a function of molecular chlorine flux increase rapidly at first. However unlike the Si yield, this fast increase is followed by a gradual increase at fluxes higher than 10@super 1@@super 5@ molecules per cm@super 2@. The direct detection of etch products results mechanistic details that can be compared to recent molecular dynamic simulations.

9:00am **PS-FrM3 Recombination of Halogen Atoms on Surfaces**, ***J.W. Coburn,*** *G.P. Kota, D.B. Graves,* University of California, Berkeley **INVITED**

The recombination of halogen atoms [F, Cl, Br] has been measured as a function of temperature on a variety of surfaces [Si(111), poly-Si, WSi, W, quartz, photoresist, stainless steel, anodized Al]. Beams of halogen atoms were directed onto the surface under study in an ultrahigh vacuum system and the species evolved and reflected from the surface were detected with a differentially pumped modulated beam mass spectrometer. Since the halogen atoms undergo only a single collision with the surface, low recombination coefficients [less than a few percent] cannot be measured. In all cases studied, the recombination coefficient decreased with increasing surface temperature. The magnitude of the recombination coefficient for the various gas-surface combinations studied varied from as large as 0.8 to below the limit of our measurement [a few percent]. The recombination of Cl atoms on poly-Si was substantially larger than on Si(111). In general, the recombination coefficient for F atoms was much less than for Cl and Br atoms. The data is interpreted in terms of an incident atom or a moving physisorbed atom recombining with an immobile weakly chemisorbed atom.

9:40am **PS-FrM5 Removal of Si-O, Si-C and Si-F by Hydrogen Bake after Reactive Ion Etching on the Silicon Surface**, ***Y.-B. Kim,*** *M. Caymax, H. Bender, S. Vanhaelemeersch,* IMEC, Belgium

In order to remove the damage/contamination left by Reactive Ion Etching (RIE) in a fluorocarbon chemistry on Si surface, a cleaning process consisting of an oxygen plasma/HF/H@SUB 2@ bake has been developed. ARXPS found Si-F, Si-C, Si-O and C-C/H bonds under the CF@sub x@ residues after RIE. Oxygen plasma formed a 2 nm thick film of fluorinated oxide on the RIE samples, removing the CF@sub x@ and C-C/H. A 2 % diluted HF dip for times between 10 and 200 s of the samples treated in RIE/oxygen plasma could not remove the Si-C, Si-F and Si-O. Next, the samples processed in RIE/O-plasma/HF were baked for 10 min at different temperatures (500 - 900 °C) in 1 bar of molecular hydrogen followed by quantitative XPS measurements. Up to 600 °C, no significant change in Si-C and Si-F was detected. Si-F and Si-C bonds decreased from 700 °C on and disappeared completely at 800 °C (Si-F) resp. 900 °C (Si-C). Si-O, which is abundantly present, is stable up to 800 °C, and abruptly decreases at 900 °C. AFM and MIR spectra respectively showed that the surface roughness decreases abruptly and the surface was reconstructed to a (2x1) dimer structure after a 900 °C anneal. A possible mechanism explaining these observations will be presented. Si-F and Si-C are formed by dissociation of the fluorocarbon radicals on the top surface and by insertion of the F and C into the upper atomic layers of the Si lattice by reactive ion mixing during the RIE. The observation that Si-O is removed very slowly by HF dipping indicates that O probably also gets buried into the Si matrix during the RIE. F is removed during hydrogen annealing by formation of the volatile HF at rather low temperature. The oxygen bonds are removed at 900 °C due to the consumption of the silicon surface atom on the Si-O sites by the well known reaction between Si and SiO@sub x@ resulting in volatile SiO. C is also removed at this temperature by its reaction with O into the volatile CO or CO@sub 2@.

10:00am **PS-FrM6 Characterisation of Self-aligned Contact Etch Processes using X-ray Photoelectron Spectroscopy, Time-Of-Flight SIMS, and Optical Emission Spectroscopy**, ***F.H. Bell,*** Siemens AG, Germany*; T. Lill,* Applied Materials*; A. Cuthbertson,* Siemens Microelectronics Ltd, England*; U. Scheithauer, R. Treichler,* Siemens AG, Germany

The self-aligned contact process (SAC) is one of the key technologies for 64M DRAM fabrication and beyond. The oxide etch process relies on C@sub 4@F@sub 8@/CO/O@sub 2@ gas mixtures to provide high selectivity between oxide and the nitride barrier layer. Critical manufacturing issues are etch stop caused by fluorocarbon polymer deposition and shorts between bitline conatcts and gate due to insufficient oxide to nitride selectivity. The robustness of the process is strongly influenced by the ratio of the C@sub 4@F@sub 8@, CO, and O@sub 2@ gases. In order to understand the mechanism of the selective oxide to nitride etch, we analysed the oxide and nitride surfaces after etching using x-ray photoelectron spectroscopy (XPS) and time-of-flight SIMS. XPS results show that the composition of the fluorocarbon polymer film on nitride is only slightly influenced by the CO and O@sub 2@ gas flows whereas the thickness of the polymer film strongly decreases with oxygen addition. TOF SIMS analyses show that the higher the CO flow the more carbon is implanted into the nitride barrier layer. Since the nitride etch rates decrease as a function of CO flow and increase with oxygen addition, the selectivity between oxide and nitride is found to depend on two mechanisms: the passivation of the nitride barrier layer by formation of a fluorocarbon polymer film and the implantation of carbon in the nitride caused by the CO gas in the SAC etch chemistry. Due to the small open area of the SAC process, optical emission spectroscopy studies were performed to improve end point detection and thus establish a robust production process.

[1] **PSTD Coburn-Winters Student Award Finalist**

10:20am **PS-FrM7 Experimental Investigation of the Respective Roles of Oxygen Atoms and Electrons in the PECVD Deposition of SiO@sub 2@ in O@sub 2@/TEOS Helicon Plasmas**, ***A. Granier***, *C. Vallée, A. Goullet, K. Aumaille, G. Turban,* Institut des Materiaux de Nantes, France

The respective roles of electrons and oxygen atoms in the plasma enhanced chemical vapor deposition of SiO@sub 2@-like films are investigated in a rf helicon oxygen/tetraethoxysilane (TEOS) plasma. The O atom density (a few 10@super 13@ cm@super -3@) and flux are monitored by actinometry and the electron density (a few 10@super 10@ cm@super -3@) by combination of optical emission spectroscopy (OES) and Langmuir probe analyses. The variations of the electron and atomic oxygen densities are studied as a function of the rf power (up to 500 W), the pressure (1-25 mTorr) and the organosilicon fraction in the O@sub 2@/TEOS plasma, simultaneously to the measurement of the deposition rate (using in situ ellipsometry) and analysis of the deposited films. The incorporation of ethoxy and silanol groups is determined from infrared spectroscopy. The refractive index and density of the films are deduced from UV-visible spectroscopic ellipsometry and gravimetric measurements respectively. It is shown that the TEOS fragmentation and the deposition rate are strongly related to the electron density while the main role of oxygen atoms is the etching of the organic part of the growing film, and not to dissociate the organosilicon molecules. In order to gain insight into the etching of the growing film by oxygen atoms, organosilicon films freshly deposited in a TEOS rich plasma are exposed to a pure oxygen plasma. During this post-exposure to an oxygen plasma, the film and the plasma are analyzed by ellipsometry and OES respectively : the film etching is clearly evidenced by the significant decrease in film thickness and the emission from CO, OH and H excited species which are related to the CO, CO@sub 2@ and H@sub 2@O etching products. It is furthermore shown that the film undergoes structural modifications over several ten nanometers.

10:40am **PS-FrM8 Surface Chemistry Mechanism of Oxide Etching by High Density C@sub 2@F@sub 6@ Plasma**, *J. Feldsien, T. Panagopoulos,* ***D.J. Economou***, University of Houston

Fluorocarbon plasmas have been studied extensively because of their use in selectively etching oxide over silicon. It is widely known that these plasmas produce unsaturated fluorocarbon radicals that may polymerize on surfaces in contact with the plasma. Oxide surfaces exposed to intense ion bombardment, on the other hand, are etching. More work remains to be done to understand the mechanisms that produce the observed behavior. In this work, a comprehensive surface chemistry model was developed to understand the mechanism of etching or deposition on oxide surfaces exposed to a high density C@sub 2@F@sub 6@ plasma. The surface chemistry model in combination with a gas phase plasma chemistry model developed by E. Meeks and J. Johannes of Sandia National Labs was implemented in the Modular Plasma Reactor Simulator (MPRES) to study oxide etching and uniformity under typical processing conditions. Simulation results on etch rate and uniformity as a function of source power, bias power, and pressure were consistent with experimental data. The transition from polymerization to etching as the ion bombardment energy (bias power) was increased was also captured by the simulation. Under low pressure conditions (several mtorr) the ion flux peaked at the wafer center while the neutral flux peaked at the wafer edge. Under such conditions, the oxide etch rate was edge fast. This supports the important conclusion that oxide etching is ion driven but neutral dominated. Surface coverages by important species and their interrelation to etch or deposition rate will also be discussed. This work was supported by Sandia National Laboratories/SEMATECH.

11:00am **PS-FrM9 Large Positive Silicon Ion Clusters in a Remote Silane Plasma**, ***W.M.M. Kessels***, *C.M. Leewis, M.C.M. van de Sanden, D.C. Schram,* Eindhoven University of Technology, The Netherlands

We report on the production of hydrogen poor cationic silicon clusters Si@sub n@H@sub m@@super +@ with up to ten silicon atoms in an expanding argon-hydrogen-silane plasma having implications for hydrogenated amorphous silicon films deposited by remote deposition techniques. It is shown that these cationic clusters are inevitably created by silane ions initiating chain reactions with silane when the product of silane density and geometrical path length is large. The initial silane ions are, in the plasma under consideration, produced by dissociative charge exchange between argon and hydrogen ions, emanating from the thermal plasma source, and silane. The deposition itself is dominated by SiH@sub 3@-radicals created by hydrogen abstraction from silane by atomic hydrogen emanating from the source and this has been determined by appearance potential mass spectrometry. The small hydrogen content (the clusters contain dominantly one hydrogen atom) in comparison with, e.g., ions in conventional rf silane plasmas is attributed to the high gas temperature due to the thermal plasma source used. The observation proves furthermore that the often quoted rates for the chain reactions of Mandich and Reents@footnote 1@ are not appropriate in this type of plasmas as even ions with more than six silicon atoms have been observed to a large extent. Moreover, a simple computer code showed that the rates for the chain reactions are not heavily depending on the number of silicon and hydrogen atoms present in the ion in contrast to their results. The contribution of the ions to film growth as determined from a combination of mass spectrometry and Langmuir probe measurements will be presented for various conditions and the influence of the ion clusters on the hydrogenated amorphous silicon film quality will be discussed. @FootnoteText@ @footnote 1@ See, e.g., W.D. Reents, Jr. and M.L. Mandich, Plasma Sources Sci. Technol. 3, 373 (1994).

11:20am **PS-FrM10 Surface Chemistry of NF@sub 3@ Plasma and Si Surface Interaction**, ***T.W. Little***, University of Washington; *A. Endou, A. Miyamoto,* Tohoku University, Japan; *M. Kitajima,* National Research Institute for Metals, Japan; *F.S. Ohuchi,* University of Washington

As an etchant gas, nitrogen trifluoride (NF@sub 3@) has become a viable contender to such mainstays in the semiconductor industry as carbon tetrafluoride (CF@sub 4@) and other perfluorocarbon compounds (PFCs) for certain plasma etching applications involving silicon (Si). Despite the technological importance of NF@sub 3@, there have been almost no studies on the interaction of NF@sub 3@ with Si from a surface science point of view. We have used x-ray photoelectron spectroscopy (XPS) and other diagnostics to determine the chemistry of interaction of NF@sub 3@ and Si surfaces. Although XPS results for the Si 2p core level are similar to those found for other etchants, we have seen unusual behavior in the F 1s core level and F 2s quasi-core level spectra. In addition to a F peak resulting from Si-F bonds, there are significant high-binding energy components which indicate that F is assuming a more positive or even neutral charge. The appearance of these peaks is closely related to both the type and amount of diluent gas. Upon heating, the high binding energy components are seen to disappear. These results lead to the supposition that F may be incorporated into the Si lattice as a result of an ion bombardment damage mechanism. While XPS is sensitive to changes in local chemistry, we have also applied a novel, in-situ Raman scattering technique which is sensitive to plasma surface interactions before they have progressed to the state in which chemical changes can be measured by XPS. The results of these measurements are described and compared with results obtained from XPS and other analytical techniques. In an effort to understand the energetics of F interaction with the Si lattice, we have also used cluster calculations to determine the most likely F sites.

11:40am **PS-FrM11 Operating High Density Plasmas in a Low Density Range : Applications to Metal Etch Processes**, ***P. Czuprynski***, France Telecom CNET/DTM/TFM, France; *O. Joubert, L. Vallier,* France Telecom CNET, France; *M. Heitzmann,* CEA LETI, France; *N. Sadeghi, J.P. Booth,* CNRS, France

In metal etching where complicated and thick metal stacks have to be etched on severe topography, selectivity between metal and resist is a critical problem. In practice, using standard Cl@sub 2@/BCl@sub 3@ etching chemistries and inductively coupled plasma sources (ICP) dedicated to metal processes, metal/resist selectivity higher than 3 are difficult to obtain. In this paper, we present a new way of operating high density plasma sources which greatly improve the selectivity issue of metal etch processes. The principal of the technique is to operate a high density plasma source in a low density mode (by strongly decreasing the RF power injected in the source, typically by a factor of 4) while keeping unchanged the RF power injected in the chuck to bias the wafer. Different techniques are used to compare the low density and high density modes. First, optical emission techniques are used to compare the dissociation efficiency of both modes and therefore get some information on the relative fluxes of Cl@sub 2@ and Cl species in the discharge. The ion current density (J@sub i@) and ion energy are also measured when the plasma source is operated in the low and high density modes (using identical chuck power conditions). The ion current density is measured using a new type of electrostatic probe whereas ion energy is simply estimated by measuring the self-bias voltage in the matching network of the chuck. The influence of low and high density modes on metal etch processes are evaluated using Cl@sub 2@/HCl chemistries. A strong increase in resist/metal selectivity is measured when the source is operated in the low density mode while perfectely anisotropic etching profiles of the metal stacks are still obtained. Finally, a simple model taking into account the chlorine coverage on the resist surface (as measured by in situ XPS), the ion density and ion energy is

proposed to describe the resist etching rate. This simple model is useful to explain why operating ICP sources in a low density mode allows the resist consumption to be strongly decrease during etching processes. @FootnoteText@ This work has been carried out within the GRESSI consortium between CEA-LETI and France Telecom-CNET.

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