Monday Morning, November 4, 2002

Manufacturing Science and Technology
Room: C-109 - Session MS+SE-MoM

In-Situ Monitoring and Metrology for Coating Growth and Manufacturing
Moderator: A. Diebold, International Sematech

8:20am **MS+SE-MoM1 Product Development and Yield Enhancement through Failure Analysis of Integrated Circuits with Scanning Capacitance Microscopy**, ***P. Tangyunyong***, *C.Y. Nakakura*, Sandia National Laboratories

Scanning capacitance microscopy (SCM) has become a widely used metrology tool in the microelectronics industry due to its ability to measure two-dimensional free carrier profiles with nanometer-scale resolution. To date, SCM has been used primarily to characterize source/drain formation by imaging cross-sectioned, metal-oxide-semiconductor field effect transistors (MOSFETs). We have extended the role of SCM in our Fab from an off-line research instrument to a routinely-used failure analysis tool, active in providing feedback in new product development, process validation, and yield enhancement. The SCM measurement can be performed on any two-dimensions of the sample, thus providing unique information that cannot be obtained with other analysis techniques. This information has been instrumental in helping to identify several yield-limiting defects in our CMOS device product line. In addition, SCM measurements are performed in-house with quick turnaround, yielding a considerable advantage over off-site analysis techniques, such as secondary ion mass spectroscopy. The methodology for performing both top-down (parallel to the wafer surface) and cross-sectional SCM measurements will be presented. We will show, in detail, several examples of how SCM information has been used to identify the root causes of device failures and discuss some of the corrective actions taken to reduce defects and improve yield.

This work was performed at and supported by Sandia National Laboratories under DOE contract DE-AC04-94AL85000. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation for the United States Department of Energy.

8:40am **MS+SE-MoM2 Integrated CD Metrology for Poly Si Etching**, ***G.P. Kota***, *C. Lee*, Lam Research Corporation, *T. Dziura, A. Levy*, KLA-Tencor Corporation

Advanced process control (APC) is gaining widespread use because of the costs associated with 300mm wafer processing and because of the stringent control required for CD and profile due to the shrinkage of critical feature dimension. APC can be used in Feed forward, Feed back and Fault detection control modes. The KT metrology module called iSpectra is integrated on to the Lam 2300 Versys etch platform. This modular design allows for real time APC. Integrated metrology also enhances the overall equipment efficiency. A comparison of iSpectra, CD-SEM, and x-SEM results will be presented. iSpectra shows good correlation to the CDSEM measurements as well as x-SEM profiles. In addition, iSpectra repeatability is superior to conventional methods such as CD-SEM. It is common knowledge that 193nm PR shrinks during CDSEM measurements due to exposure of the PR to e-beam. This shrinkage has been measured to be up to 17nm after about 30 repeated measurements on the CDSEM. In comparison, the iSpectra measurement technique results in minimal CD shrinkage.

9:00am **MS+SE-MoM3 Metrology for Manufacturing**, ***U. Whitney***, KLA-Tencor **INVITED**

9:40am **MS+SE-MoM5 Measurements of Shallow Trench Isolation by Normal Incidence Optical Critical Dimension Technique**, ***J. Hu***, *D. Shivaprasad, F. Yang, R. Korlahalli*, Nanometrics, Inc.

Shallow Trench Isolation (STI) has emerged as one of the primary techniques for device isolation in complementary metal-oxide semiconductor (CMOS) technologies. This device isolation technology has become extremely important to satisfy the high density requirements of modern integrated circuits, It is of paramount importance to measure the critical dimensions of the STI structure. Currently used CD-SEMs cannot identify the rounding typically present at the bottom or top of the profile, and it is difficult to differentiate between the top and bottom line-width values. X-SEMs which can give the profile information require the destruction of the wafer. In this paper we present the work done on STI using the Optical Critical Dimension (OCD) technique. This technique measures line or trench profiles using Normal Incidence Polarized Reflectometry with a sensitivity to sub-50nm grating lines. In the OCD technique, a broadband polarized light beam is focused onto the grating surface, and the reflected 0th order is measured as a function of wavelength. The data obtained by measuring the grating structure gives a signature of the profile structure which is analyzed in real time using Rigorous Coupled Wave Analysis (RCWA). Since the data is fitted in real time, there is no requirement for library generation, which makes the analysis simpler and easier to extend to other structures without the need of lengthy re-generation of a new library of profile data. Data from STI wafers before and after ashing (removal of the developed resist) will be presented. Sensitivity to the oxide notching and repeatability data will also be presented.

10:00am **MS+SE-MoM6 The Evolution of Single Atomic Steps on vicinal Si(111) in NH_4F**, ***J. Fu***, National Institute of Standards and Technology, *H. Zhou,* University of Maryland, *J.A. Kramar, R. Silver*, National Institute of Standards and Technology

Determining the width of a feature or the scale in a pitch measurement with appropriate accuracy is fundamental for process control in state-of-the-art semiconductor manufacturing. To meet these needs as well as the future measurement and calibration needs of the emerging nanomanufacturing industry, the National Institute of Standards and Technology (NIST) has been pursuing research and development on techniques for the fabrication and measurement of atom-based dimensional standards. The key elements in the development of atom-based standards are the ability to prepare atomically ordered surfaces,and the ability to count the atoms making up the features of interest. One of the most difficult challenges in atom-based metrology has been the fabrication of an appropriate atomic template. Atomically ordered surfaces provide an intrinsic template which have both scale and orthogonality. Using Scanning Probe Microscopy(SPM), We have examined the surface produced by etching several different vicinal Si(111) sample in 40% NH_4F. In agreement with others, we find that deoxygenation of the etchant generally reduces the number of triangular etch pits. The formation of single atomic steps is evolved from these etch pits. These etch pits undergo nucleation, growth, merging, and corner rounding which can lead to single atomic steps. We also find that for maximum uniformity and minimum root mean square roughness, a certain minimum miscut angle is required. This angle is related to the maximum clear terrace width, which in turn is related to the relative etching rate of the step-edge sites and the terrace sites. The time evolution of the surface-smoothing etching process was also examined.

10:20am **MS+SE-MoM7 Real Time in situ Spectroellipsometry**, ***J.A. Woollam***, *B. Johs, J. Hale*, J. A. Woollam Co., Inc. **INVITED**

This talk reviews applications of spectroscopic ellipsometry for in situ monitoring and control during deposition, themal processing, and etching of surfaces and thin-films. In situ spectroscopic ellipsometry is valuable for calibrating film growth and etch rates, controlling the thickness of each layer in multi-layer structures, and investigating nucleation phenomenon. It is also useful for measuring surface and interfacial roughness, substrate and film optical constants (with and without surface oxides), alloy composition, and substrate temperature. There have been numerous challenges to implementing in situ spectroscopic ellipsometry, including how to deal with substrate wobble and the effects of windows, and how to accurately measure thickness and material properties during growth of large numbers of layers in multi-layer stacks. Solutions to these practical problems will be discussed, and example applications described.

11:00am **MS+SE-MoM9 Real Time Process Control by Spectroellipsometry**, ***D. Daineka***, *P. Bulkin, T. Novikova, B. Drévillon*, CNRS, Ecole Polytechnique, France

In situ ellipsometry is well known to be the most sensitive, non-invasive tool for monitoring and control of thin film growth. In the fabrication of optical coatings and thin films in general the refractive index of the material is usually assumed to remain constant within a single layer. With such assumption only optical thickness of the layer can be controlled. For modern complex structures, however, even insignificant variation in the refractive index can be very detrimental to the final performance of the coating. Simultaneous real-time determination of refractive index and growth rate is required in order to comply with strict specifications. If the index departs from the pre-calculated target value, one has to adjust process parameters. In PECVD such control variables are gas flows of the precursors. We report on the closed-loop control of the silicon oxynitrides deposition by in situ phase modulated kinetic spectroellipsometry using a direct numerical inversion algorithm for the real-time reconstruction of refractive index and layer thickness. This technique is tested on constant index layers as well as on graded refractive index profiles and shown to be efficient and reliable.

11:20am **MS+SE-MoM10 In-Situ Studies of the Amorphous to Microcrystalline Transition of Hot-Wire CVD Si:H Films Using Real-Time Spectroscopic Ellipsometry**, ***D.H. Levi***, *B.P. Nelson*, *J.D. Perkins*, National Renewable Energy Laboratory

In-situ real-time spectroscopic ellipsometry (RTSE) provides detailed information on the evolution of the structural and optical properties of Si:H films during growth.[1] We have used in-situ RTSE to characterize the morphology and crystallinity of hot-wire CVD (HWCVD) Si:H films as a function of substrate temperature T_s, hydrogen dilution $R=[H]/[H+SiH_4]$, and film thickness d_b. Transitions from one mode of film growth to another are indicated by abrupt changes in the magnitude of the surface roughness during film growth. The degree of crystallinity of the film can be determined from the bulk dielectric function. We have studied the growth parameter space consisting of R from 0 to 14, T_s from 250°C to 550°C, and d_b from 0 to 1 µm. For each set of R and T_s values, the structural evolution of the film can be characterized by the shape of the surface roughness thickness d_s versus bulk thickness d_b curve. In contrast to studies done by Collins et al on PECVD growth of Si:H films, our studies of HWCVD growth find no conditions where d_s remains constant after coalescence of the initial nucleation centers. Most of the films grown within the range of parameters studied exhibit a secondary nucleation and coalescence signature. The transition between a-Si:H and uc-Si:H growth is near the R=3 to R=4 dividing line. Initial coalescence of purely uc-Si:H material does not occur until R>8. We have verified the RTSE crystallinity classification using ex-situ Raman scattering.

[1] R.W. Collins, Joohyun Koh, H. Fujiwara, P.I. Rovira, A.S. Ferlauto, J.A. Zapien, C.R. Wronski, R. Messier, Appl. Surf. Sci., 154-155, 217-228 (2000).

11:40am **MS+SE-MoM11 Post-Deposition Control of Resistivity and Anisotropy in ZnO Thin Films**, ***J.S. Lewis***, *B. Stoner*, *C. Pace*, MCNC

A method for post-deposition control of the resistivity of ZnO thin films has been developed, and a method for providing anisotropic sheet resistance in the plane of the film has been demonstrated. Military needs for real-time image processing can be met using thin film analog image processor (TAIP) devices. TAIP chips provide compact and power-efficient analog processing, including high- or low-pass spatial frequency filtering. The analog spatial filters are based on the RC time constant of the circuit, and therefore require thin films with controlled, repeatable sheet resistance in the range of MΩ/sq. This range of sheet resistance can be difficult to achieve with good repeatability for inorganic films. ZnO thin films were sputtered from an undoped ZnO target by RF magnetron sputtering. The as-deposited sheet resistance of the films was in the range 5-50 kΩ/sq. Post deposition processing yielded films with sheet resistance in the range from the as deposited value to > 100 MΩ/sq. Target values of sheet resistance were obtained routinely. Using an in-situ monitor of sheet resistance during processing resulted in much better repeatability than that possible for as-deposited films. For TAIP chips, anisotropic sheet resistance in the plane of the film can allow more sophisticated algorithms for image processing. Post processing techniques were used to fabricate ZnO thin films with sheet resistance anisotropy ratios in the range of 2:1 to 25:1, and larger anisotropies should be possible. This work was sponsored by DARPA (contract no. DAAD19-00-1-0002).

Manufacturing Science and Technology
Room: C-109 - Session MS-MoA

Control Issues in Electronics Manufacturing
Moderator: G.W. Rubloff, University of Maryland

2:00pm **MS-MoA1 Process Optimizations of Electrochemically Deposited Copper Films**, *H. Simka*, ***S. Shankar***, *R.P. Chalupa*, *V.M. Dubin*, Intel Corporation **INVITED**

Electrochemical deposition (ECD) of copper interconnects in state-of-the-art microelectronic devices currently involves the use of organic additives in the electrolyte to achieve complete feature fill with good film properties. Optimization of this complex process typically requires extensive experimental efforts and time. We present a novel model-based ECD optimization approach, which involves investigations of the physical phenomena due to additive species interactions, and shape-evolution simulations of Cu films. A new model, which accounts for the transient surface interactions of additives and their effects in deposition rate, has been developed. The model uses a boundary element method (BEM) approach to solve the species diffusion equations in the electrolyte domain, and a Eulerian-Lagrangian approach to track the growing surface. The model has been successfully applied to explain two previously published, independent datasets of copper thickness SEM profiles in ECD with multi-component additive systems. A physically consistent description of the observed fill behavior at different process conditions will be presented. Factors that are critical in achieving optimal ECD Cu deposition will be discussed, including effects of feature dimensions, Cu seed-layer coverage, and process conditions. Analysis of the seed-layer requirements for good ECD performance at various feature dimensions will also be presented.

2:40pm **MS-MoA3 Real-Time Control of Ion Density and Ion Energy in Chlorine Inductively Coupled Plasma Etch Processing**, *C.H. Chang*, ***K.C. Leou***, *C. Lin, T.L. Lin, C.W. Tseng, C.H. Tsai*, National Tsing Hua University, Taiwan, ROC

The advanced semiconductor fabrication requires more tighten process monitoring and control to improve production yield and reliability. Recently, advanced process control (APC), an in-situ sensor based methodology, has been applied to achieve the desired process goals in operating individual process steps. For instance, in etching of polysilicon using chlorine discharges, in order to obtain a desired etch profiles, the process often is operated at the ion-enhanced regime where the etch rate and etched profile are strongly dependent on the total ion energy flux incident on the wafer surface. Therefore, a better process control can be achieved if one can implement the real-time control of ion energy flux in etch processing. In this study, we have demonstrated experimentally the real-time multiple-input multiple-output (MIMO) control of both ion density and ion energy in etching of polysilicon using chlorine inductively coupled plasma. To measure relative positive ion density, the optical emission at 750.4 nm from trace amounts of Ar is used which is proportional to the total positive ion density. An rf voltage meter is adopted to measure the peak rf voltage on the electrostatic chuck which is linearly dependent on sheath voltage. One actuator is a 13.56 MHz rf generator having a maximum power of 5 kW to drive the inductive coil seated on a ceramic window, along with a L-type matching network to minimize the reflected power. The second actuator is also a 13.56 MHz rf generator to power the electrostatic chuck via a matching network. The two rf generator is locked in phase. The MIMO controller is designed by using Quantitative Feedback Theory (QFT), which compensates process drift, process disturbance, and pilot wafer effect. This system has been used to etch unpatterned polysilicon and silicon oxide. The experiment results showed that the MIMO control system has a better reproducibility in etch rate and uniformity compared with current industrial practice.

3:00pm **MS-MoA4 Mathematical Approaches to Optimal Control of Transient Enhanced Diffusion**, ***M.Y.L. Jung***, *R. Gunawan, R.D. Braatz, E.G. Seebauer*, University of Illinois

Excessive transient enhanced diffusion (TED) of boron in silicon during rapid thermal annealing has been a major inhibitor to forming ultrashallow junctions for CMOS device applications. TED typically gives rise to a trade-off between junction depth X_j and sheet resistance ρ as a function of process variables. For example, increasing the ramp rate β or decreasing the maximum spike temperature T_M decreases X_j but increases ρ. This tradeoff suggests there are optimum values of β and T_M to produce the best X_j and ρ. The optimization of the temperature program is posed as a minimization problem with the objective function Φ, which is a function of the junction depth and the sheet resistance. The objective is selected such that: $\Phi=X_j(T(t)) + w\rho(T(t))$ where w is a weighting factor. The constrained minimization problem is solved using sequential quadratic programming. Although current technology employs linear temperature trajectories, different parameterizations of the temperature program are used in the optimization to elucidate the true optimal trajectory. The rate of cooling is also included in the parameterization. All these calculations are performed using the process simulator FLOOPS. We describe how the kinetic parameters in this simulator were obtained using firmly grounded procedures for estimating rate parameters using the Maximum Likelihood Method together with multivariate statistics to quantify accuracy. We also describe a rigorous parameter sensitivity analysis by the finite difference method to investigate TED model behavior. These approaches lead to vast improvements in the ability of simulations to match experiment.

3:20pm **MS-MoA5 Spatially Programmable Reactor Design: Toward a New Paradigm for Equipment Effectiveness**, ***Y. Liu***, *J. Choo, L. Henn-Lecordier, G.W. Rubloff, R.A. Adomaitis*, University of Maryland

Conventional single-wafer CVD reactor designs employ showerhead gas inlets which distribute impinging gases across the wafer in an attempt to achieve across-wafer process uniformity. However, it is difficult to maintain acceptable manufacturing uniformity as process parameters are changed, or to compensate for equipment asymmetries that influence uniformity. We have developed a new approach which exploits spatial programmability of impingment gas flux and stoichiometry, using a multi-segment showerhead design that accommodates gas inlet, exhaust, and sensing in each element of a 2-D array, with two goals: (1) to achieve across-wafer uniformity at any desired process design point; and (2) to intentionally introduce across-wafer nonuniformity so as to carry out multiple experiments on a single wafer (then followed by retuning to achieve uniformity at the optimized process design point). We have constructed a three-segment prototype for initial proof-of-concept, parameter identification, and model validation. Experimental results for W CVD demonstrate both inter-segment and intra-segment deposition rate tunability, in accord with expectations from modeling and simulation. Spatially programmability of reactor design, if scalable to higher integration levels with effective sensing, actuation, and control systems, could bring forth a new paradigm in equipment design that enables rapid optimization, higher process performance at high uniformity, and design scalability to larger substrates and multiple technology generations.

3:40pm **MS-MoA6 Monitoring and Control of Binary Gas Mixtures from Solid Phase MOCVD Sources using an Acoustic Sensor**, ***L. Henn-Lecordier***, *J.N. Kidder, G.W. Rubloff*, University of Maryland

In-line acoustic sensors have been used for several years in MOCVD source delivery systems to monitor and control the upstream composition of binary gas mixtures obtained from temperature- and pressure-controlled "bubbler" vessels. Since the vapor pressures of some commonly used MOCVD solid sources is low, extending into the sub-Torr range, it becomes difficult to maintain a constant - but minute - concentration of reagent in a high flow of carrier gas. In this study, an Inficon Composer acoustic sensor was implemented to measure and control the concentration obtained from two solid phase sources using H2 as a carrier gas, including (1) trimethylindium (TMI), which is used to grow GaInAs III-V compound semiconductors for optoelectronics, and (2) bis(cyclopentadienyl) magnesium (Cp2Mg) which is used in part as a p-type doping element in nitride-based compound semiconductors for blue LED's. Both sources are crystalline solids with low vapor pressures (2.5 and 0.04 Torr at 25°C respectively for TMI and Cp2Mg), which causes unstable sublimation/delivery rates and associated variability in composition and lattice mismatch. Using the acoustic sensor, reagent levels as low as 1.E-4 mol % in H2 were monitored and found in close correlation with the expected concentrations over a broad range of total pressure from 500 down to 60 Torr. This sensitivity suggests that source delivery control may be achievable to control (i.e., compensate for) variations in source delivery rate, e.g., adjusting the flow of the carrier gas through the source, diluting the binary mixture downstream of the source, or adjusting the gas density in the source.

4:00pm **MS-MoA7 Dynamic Simulation and Optimization at the Unit Process Level for Environmentally Benign Semiconductor Manufacturing**, ***S. Cho***, *W. Lei, G.W. Rubloff*, University of Maryland

Environmentally benign semiconductor manufacturing requires methodologies which enable co-optimization of manufacturing and technology metrics (such as process cycle time, consumables costs, and product quality) along with environmental (ESH) metrics. We have investigated this challenge at the unit process level, focusing on Cu CVD unit process and equipment, using a physically-based dynamic simulation approach which takes into account the process recipe and resulting time-dependent behavior of vacuum and gas flow, heat transfer, reaction chemistry, and equipment components and control systems. Higher temperature and pressure yield reduced cycle time and precursor consumption, producing a "win-win" situation for manufacturing and ESH metrics. In contrast, changes in precursor flow rate produce trade-off situations between these metrics; at higher temperatures, however, significant gain in precursor consumption is indicated at lower flow rate, with relatively small cycle time penalty. Energy consumption per unit film thickness is substantially reduced at higher temperature because the deposition rate of the thermally activated CVD process increases faster with temperature than does the heating power required at typical process conditions. These results at the unit process level demonstrate that the dynamic simulation approach (1) provides insights into complex physical/chemical system behavior and quantitative estimates for tradeoff analysis, and (2) reveals "win-win" situations in which ESH and manufacturing benefits may be achieved together. This work is supported by the U. Arizona NSF/SRC Center for Environmentally Benign Semiconductor Manufacturing.

4:20pm **MS-MoA8 Data Handling in Semiconductor Manufacturing: Overall Approach to Correlate Yield, Process and Equipment Parameters**, *M. Horn, H. Melzner, D. Knobloch,* ***F.H. Bell***, Infineon Technologies AG, Germany

Yield improvement in semiconductor manufacturing depends on several aspects. Major challenges are the robustness of design rules, improvement of the design for testability and stable manufacturing processes. For the later one, advanced process control (APC) featuring run-to-run control and Fault Detection and Classification (FDC) is seen as the most powerful technique to improve the in-line stability. However, correlation between yield (such as threshold voltage, saturation current, die functionality and reliability issues), process and equipment parameters suffer from economic handling of the huge amount of data. An overall approach from end-of-line electrical measurements to on-line process and equipment parameter detection is needed in order to simplify the data analysis. We show how the data analysis can be simplified using data extraction techniques, such as principal component analysis, that pre-selects the most significant yield related parameters and separates yield detractors with respect to sporadic and chronological events. These data can then be used to find possible root causes in process and equipment. Consequently, the APC parameters can then (1) be weighted towards yield significance and (2) be used to define the parameter set for run-to-run control and fault detection and classification. We will discuss examples that demonstrate how deviations in process and equipment parameters detracts yield, may cause reliability problems or does not influence yield and reliability at all. Examples are taken from aluminum metallization and EPI-Centura SiGe deposition processes.

4:40pm **MS-MoA9 Improved Tool Utilization and Process Capability Through Improved Flow Verficiation Technique**, ***S.A. Tison***, *S. Lu*, Mykrolis Corporation

Critical processes require accurate and reproduceable chemical delivery to acheive the necessary process capabilities. Continues reductions is device scaling requires improved process capabilities for high aspect ratios.[1]. Many dry etching processes require highly accurate and reproduceable delivery for flows below 10 sccm.[2] Historically, gas delivery reproduceability was acheived using rate-of-rise chamber verification techniques. Two of the most common techniques are refered to as "Flow Verification" and "Flow Cal". These techniques use the chamber as an accumulation tank and measure the pressure rise with time. Through the use of the gas equation of state they derive the average delivered gas flow. With the introduction of 300 mm processes the chamber volumes have increased and some critical gas flows have decreased. These effects have resulted in long times to complete the rate-of-rise measurements with the subsequent reduction in tool availability. Data is presented which shows that improved high resolution capacitance diaphragm gages can be used to make the necessary measurements with lower accumulation pressures and improve equipment availability. For a typical etch system the "Flow Verification" sequence can be reduce by one hour per chamber. These process improvements are enabled by reducing uncertainies associated with parasitic effects such as thermal transpiration[3] and other gage nonlinearities.

[1] J. Givens et al., J. Vac. Sci. Technol. B12, 427 (1994)
[2] M. Matsui et al., J. Vac. Sci. Technol. A20, 117 (2002)
[3] K. Poulter et al., Vacuum, 33, 311 (1983).

Manufacturing Science and Technology
Room: C-109 - Session MS-TuM

Beyond Planar CMOS: Manufacturing Issues
Moderator: S Shankar, Intel Corp.

8:20am **MS-TuM1 A Systems Approach to Microelectronics**, ***J. Heath***, University of California, Los Angeles **INVITED**

In this talk I will present progress toward the fabrication of a molecular electronic computing machine, and I will discuss concepts related to machine architectures, including multiplexing and demultiplexing architectures for connecting the nano-dimensions of chemical assembly with the sub-micrometer dimensions of lithographic patterning. I will also discuss working devices and circuitry based on molecular mechanical switching complexes, as well as 3-terminal molecular electronic FETs for achieving gain. Finally, I will present patterning techniques for achieving bit densities in the range of 10^{11} to 10^{12}bits/cm^2.

9:00am **MS-TuM3 Integrated Circuit Technology Scaling: From Conventional CMOS to the Nanoscale Era**, ***P. Zeitzoff***, International SEMATECH **INVITED**

Integrated Circuit (IC) scaling per Moore's Law has been the cornerstone for IC industry growth for the last 35 years. Based on the projections in the International Technology Roadmap for Semiconductors (ITRS), we will examine the MOSFET scaling envisioned to sustain Moore's law for the next 15 years, during which the current MOSFET physical gate length of about 65 nm is expected to be scaled to about 9 nm. Issues discussed include the scaling of MOSFET performance, leakage, and power dissipation, as well as key innovations to enable the scaling. These include the potential utilization of high-k gate dielectrics, metal gate electrodes, and innovative source/drain (S/D) techniques such as raised S/D. Also, in the later stages of the ITRS, non-conventional, non-planar CMOS devices such as ultra-thin-body, fully depleted, double-gate MOSFETs may be utilized to overcome the limitations of conventional planar bulk CMOS transistors when the physical gate length is scaled to 25 nm or less.

9:40am **MS-TuM5 Nanoelectronics - Feast or Famine?**, ***J.A. Hutchby***, *V. Zhirnov, G. Bourianoff*, Semiconductor Research Corporation **INVITED**

Many concepts have been proposed to provide new means for information processing technologies as the industry standard CMOS MOSFET approaches its fundamental limits of scaling. Some concepts propose use of a particular nanotechnology to replicate the function of a silicon transistor albeit on a much smaller scale. Much of the known circuit and system architecture concepts may well be applicable in this new paradigm. Examples of this category include carbon nanotubes and molecular electronics. Other concepts(e.g. Quantum Computing and Quantum Cellular Automata) offer completely new paradigms for information processing, and will require new concepts and infrastructure to architect the desired systems functions. In this paper, the authors will discuss some of the more advanced candidates for new information processingparadigms and will show one concept for there possible relationship to silicon CMOS at the end of the current SIA Roadmap.

10:20am **MS-TuM7 Beyond Planar CMOS. A Reliability Perspective**, ***J. Maiz***, Intel **INVITED**

The aggressive scaling of the semiconductor technology continues relentlessly in order to satisfy the performance roadmap expectations created by "Moore's Law". The scaling of the planar CMOS transistor has been central to achieving past performance gains and remains as the main approach to realize the performance roadmap for at least the next decade. Concerns have been raised however, about the extendibility of this "evolutionary" approach because of the many integration, power and reliability challenges posed by the required use of exotic materials and extreme dimensional reductions. A number of companies and research institutions are looking into possible alternatives ranging from dual gate and FINFET transistors which still look & feel like CMOS devices, to more speculative and exotic solutions including quantum devices, molecular & organic transistors, novel non-volatile memory schemes, and carbon nanotube devices. Limited information exists on the reliability of such devices. This paper will discuss some of the key learnings reported, as well as speculate over the likely failure modes & mechanisms present for the more exotic configurations based on the extensive learning accumulated on the present planar CMOS devices and associated materials.

11:00am **MS-TuM9 Fabrication of Double-Gate Field Effect Transistors at the Limit of Device Scaling**, ***H.-S.P. Wong***, IBM T.J. Watson Research Center **INVITED**

As silicon CMOS devices scale into the nanometer regime, the material set and device structures employed by conventional field-effect transistors (FETs) are beginning to reach their limits. One way to extend the scaling of the FET towards smaller gate lengths (less than 20 nm) is to employ the double-gate device structure.[1] While the concept and the device physics of the double-gate FET has been explored for many years,[2] the fabrication of the double-gate FET remains difficult.[3] Self-alignment of the two gates with respect to each other and to the source and drain doping regions present a very difficult fabrication challenge. In addition, the thin silicon channel thickness required (5 to 10 nm) becomes a key manufacturing challenge as well as a unique opportunity to study fundamental device physics. This paper will review the history and state-of-the-art in double-gate device development, including the planar,[4,5] vertical(VRG),[6] and FinFET[7,8] device configurations. This paper will also review the device physics considerations which drive technology progress from SOI to the ultimate limit of FETs, highlighting the role that double-gate FETs will play in the future.

[1]H.-S. P. Wong, D. Frank, P. Solomon, H.J. Wann, J. Welser, Nanoscale CMOS, Proceedings of the IEEE, p. 259, 2001.
[2]T. Sekigawa et al., Calculated threshold voltage characteristics of an XMOS transistor having an additional bottom gate, Solid State Electronics, p. 827, 1984.
[3]H.-S. P. Wong, Beyond the Conventional Transistor, IBM J. Research and Development, p. 133, 2002.
[4]H.-S. P. Wong et al., International Electron Devices Meeting, p. 427, 1997.
[5]K. Guarini et al., International Electron Devices Meeting, p. 425, 2001.
[6]S.-H. Oh et al., International Electron Devices Meeting, p. 65, 2000.
[7]Y. Choi et al., International Electron Devices Meeting, p. 421, 2001.
[8]J. Kedzierski et al., International Electron Devices Meeting, p. 437, 2001.

Plasma Science
Room: C-105 - Session PS+MS-TuM

Plasma Diagnostics and Sensors
Moderator: R.J. Shul, Sandia National Laboratories

8:40am **PS+MS-TuM2 High-energy EEDF Tail Detection in High-frequency Discharges**, ***J. Kudela***, *K Suzuki, Y. Nakagawa, Y. Numasawa*, ANELVA Corporation, Japan, *T. Beppu*, RITE, Japan

It is well-known that the enhanced high-frequency (HF) fields in the oscillating plasma sheaths can lead to generation of high-energy electrons. At sufficiently low gas pressures, this phenomenon is crucial for the discharge maintenance. However, the phenomenon may also cause the discharge instabilities. The detection of the high-energy tail in the electron energy distribution function (EEDF) in HF discharges is, therefore, of a particular interest from the scientific point of view. It is also important from the technological point of view. The high-energy electrons are determining factor in processing plasmas affecting the discharge chemistry in the plasma volume, and on the processing surface as well. Moreover, on the processing surface, the high-energy electrons may also be responsible for undesired physical processes like charge damage. In our work, we illustrate the detection of high-energy electrons by electrostatic probes in HF discharges at two different frequencies, 2.45GHz and 60MHz. In the microwave band (2.45GHz), the detection of the high-energy electrons is rather simple and it requires only direction-sensitive probes.[1] Similar technique is applied to the VHF band (60 MHz) discharges. In these discharges, however, a proper probe compensation is necessary. The conventional compensation methods, which are based on sensing floating potential fluctuations around the probe tip, lose information about the EEDF tail. We propose a method that can lead to detection of high-energy electrons, as well as to the diagnostics of the VHF discharges. This work is supported by NEDO.

[1] J. Kudela, T. Terebessy, and M. Kando: Hot electrons and EEDF-anisotropy in large-area surface-wave discharges; Proc. IV Int. Workshop Microwave Discharges: Fundamentals and Applications, Sept. 18-22, 2000, Zvenigorod, Russia; ed. Yu.A. Lebedev (Yanus-K, Moscow, 2001), p.63.

9:00am **PS+MS-TuM3 Coupled Diagnostic Studies of Plasma Etch Byproducts**, ***M.T. Radtke***, *D.B. Graves, J.W. Coburn*, University of California Berkeley

Plasmas used for etching invariably include species that originate at surfaces. Etch byproducts commonly play a major role in plasma composition, in addition to influencing etch rate, anisotropy, critical dimension control, and selectivity. Etch byproducts often deposit on chamber walls, altering wall chemistry such as radical recombination reactions, and leading to the formation of particles. Chamber wall cleaning and conditioning protocols can play an important role in etch tool cost-of-ownership. For new high-k and low-k dielectrics and metal gate electrode materials, the etch characteristics and etch byproducts are usually not known. In addition to posing a challenge for feature critical dimension control and other etch objectives, the unknown etch byproducts may pose environmental, health and safety hazards. We reports studies using an inductively coupled plasma reactor equipped with a cooled, rf-biased chuck, a downstream FTIR spectrometer, a quartz crystal microbalance, a Langmuir probe, an ion flux wall probe, an ion mass spectrometer, a separate threshold ionization mass spectrometer for neutral radical detection, and optical emission spectroscopy. We have employed this system to measure etch byproducts and etch byproduct transport for a range of new high-k and low-k dielectric materials as well as candidates for metal gate electrodes. We illustrate the use of coupled plasma diagnostics for ZrO_2/Cl_2, SiO_2/CF_4, RuO_2/O_2, HfO_2/Cl_2, and $Si/Cl_2/O_2$. In particular, detection and identification of low volatility byproducts can be challenging, and often require combining information from the ion mass spectrometer, the neutral mass spectrometer, film composition measurements on the quartz microbalance, optical emission spectroscopy, and the downstream gas composition.

9:20am **PS+MS-TuM4 Two-Dimensional Ion Flux Distributions on the Wafer Surface in Inductively Coupled Plasma Reactors**, ***E.S. Aydil***, *T.W. Kim*, University of California, Santa Barbara

A two-dimensional array of planar Langmuir probes manufactured on a 200 mm diameter silicon wafer was used to measure the radial and azimuthal variation of ion flux impinging on the wafer surface in various mixtures of electropositive and electronegative gases maintained in an inductively coupled plasma etching reactor. The spatial variation of ion flux in a pure Ar discharge is radially symmetric and peaks at the center of the wafer for pressures between 10 and 60 mTorr. Addition of small amounts of electronegative gases to an Ar discharge flattens the radial and azimuthal ion flux distribution and accentuates azimuthal variation due to subtle asymmetries in the reactor geometry such as pumping ports. At fixed power, pressure, and flow rate, the spatially averaged ion current density decreases with increasing mole fraction of the electronegative gases in the feed gas. In conjunction with experimental data, we developed a simple theoretical framework within which the spatial variation of ion flux in gas mixtures can be understood. Ion Flux uniformity in various binary mixtures of Cl2, He, Ar, HBr, O2, and SF6 will be discussed. Spatiotemporal variation of ion flux in presence of instabilities in SF6 discharges will be presented.

9:40am **PS+MS-TuM5 Surface Dependent Effects at the Plasma-Surface Interface**, ***G.A. Hebner***, Sandia National Laboratories **INVITED**

In a typical etching application, a number of different materials from the common silicon, and silicon oxide to more exotic nitrides and low-k materials can be located in very close proximity to each other. The interaction of these different materials through changes in the plasma chemistry, non-equilibrium surface layers and local electric field is of fundamental interest since the local chemistry and plasma properties determine the characteristics of the resulting etch profile. A number of techniques have been used to characterize etching plasmas as a function of the surface material. Plasma species such as CFx, SIFx and BCl radials have been measured as functions of the surface material and radial position using laser induced fluorescence. Those measurements show significant changes in radical species concentration for silicon, silicon oxide and ceramic surfaces. Measurements of the electron and negative ion density using a microwave interferometer and laser photodetachment also show surface dependent changes in the bulk plasma chemistry. In addition to the plasma chemistry, the sheath electric field is of interest since it's magnitude and vector guide the ion species. Of particular interest is the measurement of the material dependent surface charging, a task that is challenging considering the required spatial, temporal and electric field sensitivity. An atomic beam system combined with pulsed laser spectroscopy has been used to directly calibrate the electric field induced Stark shift of high lying energy levels. Measurements of the electric field within an inductively driven argon discharge will be discussed. The possibility of using this system to calibrate energy level shifts in other gases of technological interest to the microelectronics and lighting industry will be discussed. This work was supported by the United States Department of Energy (DE-AC04-94AL85000).

10:20am **PS+MS-TuM7 Monitoring Sheath Voltages and Ion Energies in High-Density Plasmas using Radio-Frequency Current and Voltage Measurements**, ***M.A. Sobolewski***, National Institute of Standards and Technology

The bombardment of substrate surfaces by energetic ions plays an important role in plasma etching and other plasma processing applications. To obtain optimal results, ion kinetic energies must be carefully controlled. However, measuring ion energy distributions in situ, at a wafer surface during plasma processing, is difficult or impossible. A method for indirectly monitoring ion bombardment energies would thus be useful, both as a source of information to guide process development and as a tool for process monitoring and control in manufacturing. Accurate ion energy distributions can be calculated by models of plasma sheaths if one knows the sheath voltage, the electron temperature, and the total ion flux. These parameters are in turn related to radio-frequency (rf) current and voltage signals that can be measured outside a plasma reactor, without perturbing the plasma or the process. Indeed, several different model-based methods have been proposed for using rf current and voltage measurements to determine sheath voltages and ion energies. In this study, three such methods were tested. Tests were performed in argon and CF_4 discharges at 10 mTorr, in an inductively coupled, high-density plasma reactor. All the methods were able to successfully detect changes in sheath voltages and total ion flux, and to infer the effect of these changes on ion energy distributions. However, the rf measurements are relatively insensitive to changes in the electron temperature. To obtain the most accurate sheath voltages and ion energies from rf measurements, the electron temperature should be known ahead of time, or monitored by some independent measurement technique.

10:40am **PS+MS-TuM8 Gas Temperature Effects on CF_x Kinetics in a CF_4 Inductively Coupled Plasma**, *H. Abada*, ***J.P. Booth***, *P. Chabert*, Ecole Polytechnique, France

We have used Laser Induced Fluorescence to determine CF and CF_2 radical concentrations in steady state and pulse-modulated inductively-coupled plasmas in CF_4 at 5 and 33 mTorr. The rotationally-resolved LIF excitation spectra of the CF radical were used to determine the space and time resolved gas temperature. Strong temperature gradients were observed, with the temperature reaching 800 K in the reactor center at 33 mTorr, 250 W RF power. These measurements were used to correct the LIF measurements for the dependence of the partition function on the gas temperature, providing the first reliable measurements of CF and CF_2 kinetics in this system. The concentration profiles can be used to deduce the net flux of these species from or to the reactor walls, using Fick's law but also allowing for thermo-diffusion. The steady-state CF_2 profiles showed that this species is produced predominantly at the reactor walls by CF_x^+ ion bombardment. Surprisingly, in the post-discharge the CF_2 density increases markedly for several milliseconds, before decaying slowly. We will explore the possible origins of this phenomenon, which include convection induced by gas cooling, vibrational relaxation and conversion of CF to CF_2 by chemical reaction. In contrast, the CF radical appears to be both produced and destroyed in the gas phase, and it's concentration decays monotonically and rapidly in the post-discharge.

11:00am **PS+MS-TuM9 Electron Energy Distribution in C_2F_4/CF_3I Ultrahigh-Frequency and Inductively Coupled Plasmas**, ***T. Nakano***, National Defense Academy, Japan, *S. Samukawa*, Tohoku University, Japan **INVITED**

The electron energy distribution function (eedf) is an important factor in determining radical compositions in plasmas for nanometer-scale device fabrication. In this presentation, the electron energy distribution in plasma through a C_2F_4/CF_3I mixture, which is a novel chemistry proposed for low-damaged, fine structure etching of SiO_2, is studied by trace rare gas optical emission spectroscopy (TRG-OES) and probe measurements. The integrated eedf above 13.5 eV (S_{eedf}) is evaluated from the Ar emission at 750.4 nm. The S_{eedf} exhibits a weaker dependence on the gas composition for the C_2F_4/CF_3I mixture than for the C_4F_8/Ar mixture which is conventional chemistry for SiO_2 etching. For practical etching conditions, the S_{eedf} for the C_2F_4/CF_3I mixture becomes smaller than 1/3 of that for the C_4F_8/Ar mixture in both ultrahigh-frequency (UHF) plasmas and inductively coupled plasmas (ICP). Thus, using the C_2F_4/CF_3I chemistry, low charging damage in SiO_2 etching is expected. The probe-measured electron temperature (T_e), which indicates the degree of the exponential eedf decay in the low energy, is 2.5 eV in UHF plasma through the C_2F_4/CF_3I mixture and 4.1 eV in the ICP, while S_{eedf} is twice as large in the UHF plasma as in the ICP. This suggests an eedf enhancement in the middle energy region (5-10 eV) for the ICP, which prompts the dissociation of the feedstock gases. A quantitative estimation of the eedf using a bi-Maxwellian-like function, which is crucial to understanding the relationship between the eedf and feedstock gas dissociation, is in progress. The preliminary results also support the eedf enhancement in the middle energy region for the ICP.

11:40am **PS+MS-TuM11 Dependence of Radical Densities on Fluorocarbon Feed Gases in a Dielectric Etch Plasma**, ***E.A. Hudson****, J. Luque*, Lam Research Corp.*, N. Bulcourt*, *J.P. Booth*, Ecole Polytechnique, France

Unsaturated fluorocarbon gases are increasingly important for critical dielectric etch applications. Under typical plasma etch conditions, these feed gases promote the deposition of fluorocarbon polymer films. Using process parameters to tune the polymer deposition characteristics, one can control the critical dimension and profile of the etched feature, and minimize the loss of the photoresist mask. Different unsaturated fluorocarbon gases produce different process results, for reasons which are poorly understood. In an effort to better understand these differences, the plasma radical composition has been analyzed for a range of feed gases including the unsaturated fluorocarbons octofluorocyclobutane(C_4F_8) and octafluorocyclopentene (C_5F_8), and also a saturated compound, perfluoroethane (C_2F_6). Optical emission spectroscopy (OES) and broad-band UV absorption spectroscopy (UVAS) have been used to measure radical densities in a dual-frequency, capacitively-coupled, dielectric etch reactor. Species detected include CF, CF_2, and F. Notable variations in radical densities were observed for a series of processes based on Ar, O_2, and one of the fluorocarbon feed gases. CF_2 density, in particular, showed a strong dependence on fluorocarbon feed gas. The F/CF2 density ratio increased by more than a factor of 2 when C_2F_6 was substituted for C_5F_8. For each fluorocarbon feed gas, the sensitivity to changes in the O_2 flow has been evaluated. Results suggest that the role of oxygen in controlling polymer film thickness in and around etched features is related to polymer formation as well as polymer removal.

Manufacturing Science and Technology
Room: C-109 - Session MS+MM-TuA

Manufacturing Issues in MEMS and Related Microsystems
Moderator: E.G. Seebauer, University of Illinois

2:00pm **MS+MM-TuA1 Silicon Micromachines for Science and Technology**, ***D. Bishop***, Bell Laboratories, Lucent Technologies **INVITED**

The era of silicon micromechanics is upon us. In areas as diverse as telecommunications, automotive, aerospace, chemistry, entertainment and basic science the ability to build microscopic machines from silicon is having a revolutionary impact. In my talk I will discuss what micromachines are, how they are built and show examples of how they will have a revolutionary impact in many areas of science as well as technology.

2:40pm **MS+MM-TuA3 Silicon Nano-biotechnology**, ***G. Timp***, University of Illinois, Urbana **INVITED**

Silicon nanotechnology can now manufacture logic that incorporates more than 43 million Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs) into a monolithic integrated circuit (IC). Some of these MOSFETs have a gate or control electrode that is only 130nm long with a gate oxide that insulates the control electrode from the current-carrying channel that is as thin as 1.7nm. Moreover, we have recently shown that further miniaturization is practical. We have produced nanometer-scale MOSFETs or nano-transistors with a gate electrode as shorter than 40nm and a gate oxide thinner 1nm. Inexorably, within the next ten years (according to the ITRS roadmap) the electronics industry is expected to integrate over a billion nanotransistors into a ~3-10cm2 area chip, packing about 5-10 nano-transistors/mm2. Integration on this scale, along with the facility for nanofabrication, will enabled new types of ICs. For example, we will show that it is now possible to fabricate ICs so small that they could inserted inside a living cell. Since the cell is the key to biology, such a chip combined with sensors could provide unprecedented access to it. We will also show how silicon nanofabrication technology can be used to produce sensors out of nanometer-scale pores (~2nm in diameter) in an ultra-thin glass membrane (~2nm thick), which function like ion channels in the membrane of a living cell. Such devices may ultimately be used in proteomics or for rapid sequencing of minute amounts of DNA to discover the genetic origin of a disease.

3:20pm **MS+MM-TuA5 Manufacturing Issues in MEMS and Related Microsystems**, ***B.P. Gogoi***, Motorola **INVITED**

MEMS(MicroElectroMechanical Systems) use IC(Integrated Circuit) manufacturing technology for the fabrication of sensors and actuators that utilize a wide variety of transduction principles to interact with the physical world. The three dimensional aspects of the sensor require some additional process technology that is not available in conventional IC technology. Also, since many of these sensors and actuators require the presence of intentional gaps in which mechanical motion is initiated, MEMS technology also require methods to form these intentional gaps. Using this enabling technology, a number of high volume sensors have been developed for the mainstream market in the automotive, consumer, industrial and medical segments. However, as the trend in IC manufacturing has progressed towards more shallower and planar technology, the trend in MEMS technology has moved towards high aspect ratio structures. The issues related to manufacturing of sensors and actuators using MEMS technology will be discussed. Some of the specific requirements of the process technology to enable well-controlled high volume manufacturing of sensors will be presented. In addition, examples of failure mechanisms that result from the interaction of design and the fabrication process will be discussed. The choices in the integration of these sensors and actuators with the system circuitry will also be presented.

4:00pm **MS+MM-TuA7 MEMS Technology Challenges for Volume Manufacturing**, ***V. Rao***, Intel Corporation **INVITED**

MEMS(Micro Electro Mechanical Systems) is a silicon technology for fabricating miniature mechanical devices made mostly of beams, membranes and channels. These mechanical devices are integrated with electronics to form Microsystems which find use in Communications and computing, Inertial sensing, environmental sensing and Biomedicine. MEMS devices are particularly attractive in the personal communications space because they can provide significant benefits such as energy efficiency and small footprint. However as these are high volume markets the technology must provide the required reliability and cost characteristics for these applications. In RF systems today many passive devices are discrete and off chip. MEMS technology provides a way to integrate the high value passive elements (such as switches, filters and high Q inductors) thereby reducing footprint and enhancing performance. Another example in the communication space is in the use of micromirrors for all optical switching. This is very compelling as light signals can be switched directly in the optical domain by moving mirrors avoiding the expensive Optical to Electrical to Optical conversion as is currently done. This paper will discuss some of the key manufacturing hurdles that must be overcome to realize the reliability and cost benefits that MEMS technology must meet. We will start by discussing key process modules that differentiate MEMS technology from traditional CMOS. We will then describe the stare of the art for these modules today and discuss the technological hurdles that must be addressed for future volume manufacturing.

4:40pm **MS+MM-TuA9 Manufacturing Issues of Automotive Sensors produced at Bosch**, ***M. Offenberg***, Robert Bosch GmbH, Germany **INVITED**

An ever increasing number of electronic systems in vehicles helps to increase the safety and comfort of the driver as well as to increase fuel efficiency and to reduce toxic emissions. Sensors are enabling components for the functionality of these electronic systems. Over the last decade microfabrication technologies have contributed to reduce the cost of these sensors - and thus overall system cost - while at the same time increasing their functionality and reliability. This paper describes selected micro sensors that have been successfully introduced to the market such as pressure sensors, mass flow sensors, acceleration and angular rate sensors. Manufacturing aspects and processes with and without monolithic integration are illustrated for a surface micro-machining process. The embedding of MEMS manufacturing in an existing 6-inch ASIC production environment to achieve an optimized low-cost process is described. Key process steps such as deposition of mechanical-grade thick poly-silicon layers, trench etching, sacrificial oxide etch and hermetic sealing are illustrated. Some of the key processes require dedicated equipment that was developed in collaboration with equipment manufacturer. High rate silicon deep silicon etcher in cluster tools ensure low cost of ownership. Process monitors for mechanical stress and stress gradient will be presented and manufacturing issues such as cross contamination and particle protections are discussed using inertial sensors as an example.

Authors Index

Bold page numbers indicate the presenter