Wednesday Morning, November 12, 2014

Plasma Science and Technology
Room: 305 - Session PS1-WeM

Plasma Based Ion Implantation and Ion-Surface Interactions
Moderator: Aseem K. Srivastava, Applied Materials, Inc.

8:00am **PS1-WeM1 Dosimetry Challenges for Plasma Doping and Ion Implantation**, ***Bo Vanderberg***, *L.M. Rubin, A.M. Ray*, Axcelis Technologies, Inc. **INVITED**

Plasma doping been described as a fledgling technology to complement and replace ion beam based implantation, due to its advantage in productivity given by the much higher average ion current delivered to work pieces. While productivity is an important factor in industrial applications, each technology also has to deliver appropriate dose control, and thus relies on advanced dosimetry systems to provide accurate dosage, high dose uniformity across the work piece, precise ion placement, i.e. energy and angle control, low contamination of undesired energetic and environmental species, and reliability and exception handling capability.

For commercial semiconductor manufacturing applications in particular, simultaneous compliance to each of these requirements is critical. Modern ion beam based implantation systems can provide dosimetry to meet these requirements, and we will describe some of the new technologies developed specifically for ion implantation of the most advanced semiconductor devices: fast data acquisition of multiple Faraday systems with parallel current collection, and measurement of spatial ion beam properties such energy and two-dimensional spatial and angle distribution, as well as their time dependence to monitor drift and intermittent failures.

For plasma doping to meet these standards, obstacles in terms of lack of mass-resolution, simultaneous implantation, deposition and etching, and lack of in situ beam monitoring during the plasma doping process represent formidable challenges. While some if the inherent shortcomings of plasma doping are fundamental, some techniques have been developed to address these issues, including novel Faraday systems as well as model based dosimetry with either theoretical or empirical modeling of plasma physical and chemical processes, some of which we will review.

The most difficult challenge for plasma doping is matching of dopant depth profiles of existing ion beam based implantation, where implanted dopant profiles as presented in the literature are different from their equivalent ion beam produced profiles. Without this capability, plasma doping of semiconductors is confined to a niche application space, covering less sensitive doping processes in semiconductor manufacture.

8:40am **PS1-WeM3 Ion Implantation Challenges and Applications for Future Memory Devices**, ***Allen McTeer***, Micron Technology **INVITED**

For many years memory manufacturers resisted the need to adopt implant steps that were considered mainstream in logic manufacturing in order to keep cost down. In the last few years this approach has had to change to address scaling issues. Pre-amorphization, carbon, germanium and indium implants have been adopted by most memory manufacturers for dopant profile and silicide growth control. At the same time, plasma doping was adopted to address productivity issues seen with high dose, low energy beamline implants. These changes reflect the realization that technology challenges and cost mitigation are becoming more divergent with shrinking geometries. The introduction of emerging and vertical memory devices is expanding the applications of both beamline and plasma doping techniques. This talk will discuss some of the new implant applications that could be introduced in upcoming memory devices to address process needs. This will include discussion and data review of applications related to stress control, implant damage, silicon cracking, high aspect ratio implants, hydrogenation, surface modification, dopant profile control and interface cleaning.

9:20am **PS1-WeM5 Challenges in Ion Implantation**, ***Joseph Olson***, *S. Chennadi, G. Gammel, N. Pradhan, F. Sinclair, S. Todorov, M. Welsch, R. White*, Applied Materials, Varian Semiconductor Equipment **INVITED**

Requirements on commercial ion implantation equipment grow increasingly stringent as device nodes progress. In the face of these tightening requirements the implanter designer is faced with the challenge of designing and building apparatus to measure and control process properties and then to validate improved performance. Recent examples of this process in action are discussed. (1) Precise control of the incidence angles of ions on a substrate is required for accurate placement of dopant atoms. Development to meet this need lead to advanced measurement and control systems and a powerful new technique (the 2D V curve) that produces a map of incident angles over an entire 300 mm Si substrate. The 2D V curve is explained in detail. (2) The current density in beamline implantation has potential process consequences on microuniformity, substrate charging and amorphization. The development of a beam density measurement, beam size control system and validation by examination of implanted wafers is discussed.

11:00am **PS1-WeM10 Plasma Doping Process Monitoring Diagnostics**, ***Yuuki Kobayashi***, Tokyo Electron Limited, Japan, *P. Ventzek*, Tokyo Electron America, Inc., *K. Yamashita, S. Nishijima, M. Oka, H. Ueda, Y. Sugimoto, M. Horigome, T. Nozawa*, Tokyo Electron Limited, Japan

Plasma doping is an emerging technology for the doping of next generation topographic structures such as Fin-FET extensions. Typically a dopant precursor such as arsine in injected into a plasma source where the dopants are freed from the precursor and injected into a surface that is initially amorphized by the ion flux incident on the topographic structure. As the doping process is impacted by the precursor, ion and energy flux to the substrate, it is important to have diagnostics to measure these quantities. Knowing the dose as a function of the critical measureable plasma parameters allows a model to be developed for dose monitoring and control. The model need not be physically based but could also be statistical. The challenge is coming up with simple enough diagnostics that integrate in a non-contaminating way with the plasma. Independent measurement of plasma parameters is also important as a monitor of plasma source and process stability which also impact dose. We have developed a hybrid sensor set comprising of an in-situ current and optical emission (OES) monitors that are used to correlate with dose measurements corresponding to a radial line slot antenna plasma doping process. The in-situ current monitor enables measurement of plasma density and OES provides measurement of dopant radicals. Both monitoring methods, when used together, permit detection of previously immeasurable process drift affecting doping performance. In this presentation, we describe the sensors and typical results. The relationship between dose, plasma and optical measurements is discussed in terms of a descriptive model. A physical interpretation of the results is aided by simulations of the plasma for which we present summary results.

11:20am **PS1-WeM11 Control over the Ion Flux Obtained by Sawtooth-like Waveforms in Radiofrequency Capacitively Coupled Plasmas**, ***Bastien Bruneau****, *T. Novikova, T. Lafleur, J.-P. Booth, E.V. Johnson*, Ecole Polytechnique, France

The use of Tailored Voltage Waveforms (TVWs) to manipulate the Electrical Asymmetry Effect (EAE) in a capacitively coupled plasma (CCP) chamber has been shown to be an effective technique for varying ion bombardment energy (IBE) at the surface of an electrode. It stems mainly from an amplitude asymmetry, i.e. from waveforms with different maximum and minimum. We present herein a new plasma asymmetry, obtained by sawtooth-like waveforms.

We use Particle-in-Cell (PIC) simulations to study an argon plasma excited by sawtooth-like waveforms. Using a waveform with slow rise and fast fall, we show that a fast fall leads to fast sheath expansion in front of the powered electrode, and therefore high ionization at this sheath edge. On the other hand, the slow fall leads to slow sheath expansion in front of the grounded electrode, and therefore to weak ionization at this sheath edge. This ionization asymmetry subsequently leads to an ion flux asymmetry, with up to twice higher flux on powered electrode. Because of this ion flux asymmetry, a positive self-bias develops in this plasma, leading to smaller IBE on the powered electrode compared to the grounded electrode. Therefore, the high-flux electrode also corresponds to the low-energy electrode. This property is unique, as it cannot be obtained with any of the geometrical asymmetry, amplitude asymmetry or with any mono-frequency RF excitation. We show that the ion flux asymmetry effect increases both with the number of frequencies composing the waveform, as the slope-asymmetry of the waveform then increases, and with pressure, as diffusion from one electrode to the other is hindered at high pressure. Waveforms optimizing the slope-asymmetry effect and allowing a fine and continuous control over the asymmetry are presented.

This slope asymmetry effect can be of great interest for any process using RF-CCP plasma, as one can control independently the ion flux on each electrode. For instance, one can imagine using a sawtooth-like waveform in a deposition (or etching) process. The deposition (or etching) rate can then be increased on the substrate of interest, while benefitting from a low IBE, and while keeping the up-time of the reactor high by keeping the

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*** Coburn & Winters Student Award Finalist**

maintenance-time low, thanks to the low deposition (or etching) rate on the other electrode.

11:40am **PS1-WeM12 Surface Roughening Mechanisms and Roughness Suppression during Si Etching in Inductively Coupled Cl_2 Plasmas**, ***Nobuya Nakazaki***, *H. Matsumoto, K. Eriguchi, K. Ono*, Kyoto University, Japan

As ULSI device dimensions continue to be scaled down to << 100 nm, increasingly strict requirements are being imposed on plasma etching technology. The requirements include the precise control of profile, critical dimension, roughness, and their microscopic uniformity (or aspect-ration dependence), together with that of etch rate, selectivity, and damage. Atomic- or nanometer-scale surface roughness has become an important issue to be resolved in the fabrication of nanoscale devices, because the roughness at the feature bottom affects the uniformity of bottom surfaces, which in turn leads to a recess and thus a damage to transistors in gate fabrication. Moreover, the roughness on feature sidewalls is responsible for the line edge roughness (LER) and linewidth roughness (LWR), which affect the variability for gate or channel lengths and thus the variability in transistor performance. The formation of such surface roughness is stochastic and three dimensional, which are assumed to be affected by a number of factors during processing including plasma etching.

Experimental investigations of the surface roughness of planer substrate of Si etched in inductively coupled Cl_2 plasmas have been performed, including several surface and plasma diagnostics, to gain a deeper understanding the mechanisms for surface roughening and then to find a way for suppressing the roughness during plasma etching. The experiments indicated that as the rf bias power or incident ion energy E_i is increased, the etch rate continues to increase, while the surface roughness increases and then substantially decreases at high E_i. In addition, the surface roughness at low E_i increases with etching time, while does not depend on etching time at high E_i. The analysis of the etch rate as a function of E_i and etching time, with the help of Fourier transform infrared (FTIR) absorption spectroscopy, quadrupole mass spectrometry (QMS), and classical molecular dynamics (MD) simulation, implied that by-product ions of silicon chlorides $SiCl_x^+$, whose concentration is increased in the plasma at increased E_i, play a critical role in surface roughening as well as etching at increased E_i through competitive etching and deposition. [1,2] Moreover, the pulse-bias etching through a repetitive on/off of the rf bias power also have been demonstrated to be one promising way of reducing the surface roughness during plasma etching.

[1] H. Tsuda, N. Nakazaki, Y. Takao, K, Eriguchi, and K. Ono: J. Vac. Sci. Technol. B (2014) in press.

[2] N. Nakazaki, Y. Takao, K, Eriguchi, and K. Ono: Jpn. J. Appl. Phys. **53** (2014) 056201.

12:00pm **PS1-WeM13 Ion Induced Electron Emission from Semiconductors: An Investigation into Fermi Level and Surface Electric Field Effects**, ***David Urrabazo***, *M.J. Goeckner, L.J. Overzet*, University of Texas at Dallas

A few recent publications point to the possibility of controlling the ion induced electron emission (IIEE) yield from semiconductor surfaces in real time through controlling the numbers of electrons in the semiconductor's conduction band ($n_{e,CB}$). Of course, ion bombardment induced electron emission also occurs in the plasma processing of semiconductors, and should cause differences between processing n- and p-type wafers if it truly depends upon $n_{e,CB}$. Hagstrum's Auger neutralization theory for semiconductors[1] assumes that the IIEE yield should NOT depend upon $n_{e,CB}$, and as a result most models make the assumption that the IIEE yield is independent of $n_{e,CB}$ (and the position of the Fermi level as well as temperature). To our knowledge, no one has investigated this assumption! Therefore, we have experimentally and theoretically investigated it by using and extending Hagstrum's theory as well as by measuring the IIEE yield from semiconductor samples versus doping density and type. Our results for Si demonstrate good agreement with the assumption both theoretically and experimentally. The IIEE yields of p-type, intrinsic and n-type samples are essentially the same. In direct contradiction to the theory/assumption, however; the IIEE yield for p-type Ge was measured to be 2.5 times greater than that of intrinsic and n-type samples. Precisely the opposite of what one might first expect! This result indicates that there can be other significant factors controlling the IIEE yield. One likely factor is a surface electric field. (It could have been induced by Fermi level pinning in the case of our Ge measurements, and in plasmas it could be induced by the sheath.) As a result, the new principle question becomes: Can a moderate surface electric field control the IIEE yield from semiconductors? To our knowledge, there are no unambiguous measurements answering this question either . Therefore, we will introduce a device we have designed, modeled, and begun fabricating for measuring the IIEE yield while allowing independent control over the ion flux to the surface and electric field imposed on that surface.

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[1] H.D. Hagstrum, Phys. Rev. 122 83 (1961)

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