Plasma Science and Technology
Room: 210B - Session PS+AP+SE-ThA

Advanced Ion Implantation and Plasma Doping
Moderator: Aseem K. Srivastava, Applied Materials, Inc.

2:20pm **PS+AP+SE-ThA1 Evolutionary Trends in Ion Implantation**, ***Anthony Renau***, Applied Materials, Varian Semiconductor Equipment **INVITED**

Since the 1960s and 1970s ion implantation has been used for the p- and n-type doping of semiconductors. The ability of ion implantation to abruptly alter the stoichiometry of the substrate has made it a very attractive technology for making transistors with the required drive characteristics, by accuratley manipulating dopant concentrations in the contact and channel regions. It is used to control carrier density, channel length, contact resistance, isolation and other key device attributes.

There have been significant enhancements to enable ion implant to continue to meet semiconductor doping needs. These include the development of ribbon ion beams, substrate temperature control, accurate beam angle control and novel methods for precisely varying the dose over the substrate. These improvements have also enabled the technology to be used for a rapidly growing number of non-doping applications.

Today, the majority of implants are done not for doping, but are instead used for some form of materials modification or engineering. These include, for example, strain control, pre- or post-treatments to improve some other process step, and lattice enginering for isolation or diffusion control.

In this paper we will discuss some of the improvements to the technology and the applications that have benifited from these. We will also describe how directed ribbon beam technology, similar to that used for implanters, can also be used to improve materials engineering applications as diverse as etch and CMP.

3:00pm **PS+AP+SE-ThA3 Conformal Arsenic Doping using a Radial Line Slot Antenna Microwave Plasma Source**, ***Hirokazu Ueda***, Tokyo Electron Limited, Japan, *P. Ventzek*, Tokyo Electron America, Inc., *M. Oka, Y. Kobayashi, Y. Sugimoto,* Tokyo Electron Ltd., *T. Nozawa,* Tokyo Electron Ltd., Japan, *S. Kawakami*, Tokyo Electron Ltd. **INVITED**

Doping and activation of non-planar topographic structures is important for the fabrication of functional FinFET and nanowire based devices to name a few. Conformal plasma arsenic doping of topographic (fin) structures was achieved using RLSA^{TM} microwave plasmas with low temperature annealing. To show that the arsenic concentrations were identical at the fin top and sides, dopant concentrations were measured precisely by TEM and SEM EDX for both plasma doping and subsequent annealing steps. We found that doping using plasmas generated by lower RF bias operation coincident with high microwave power was key to obtaining perfectly conformal arsenic dose/profiles after annealing. The RLSA^{TM} microwave plasma facilitates high enough electron density at the plasma generation region to supply enough reactive dopants for sufficient dose. The high plasma density plasma allows for operation in a low RF power and high process pressure regime. This regime yields ions with sufficient flux and energy for dopant integration into and redistribution around the topographic structure. At the same time low enough energy ions can be controllably accessed to ensure fin damage is eliminated. We also demonstrate optimized rf bias power of the microwave RLSA^{TM} plasma enables additional control of dopant conformality post SPM wet cleaning step. The wet clean poses a significant challenge for dose retention as cleans tend to remove oxidized or otherwise disordered silicon material. The source of dose retention is shown to be related to dopant transport through a ternary (As-Si-O) oxide layer, segregation effects and the stable nature of the oxide. The presentation will include experimental and computational results related to dose conformality and retention. Comments related to the future of plasma doping technology including advanced materials, metrology and control will round out the presentation.

4:00pm **PS+AP+SE-ThA6 Practical Application of Atom Probe to Analysis of Ion Implantation**, ***Ty Prosa***, CAMECA Instruments Inc. **INVITED**

Characterization of implanted dopants and impurity atoms within individual silicon nano-devices is critical to the semiconductor industry. While secondary ion mass spectrometry (SIMS) depth profiles achieve a high level of quantification with ion implanted standards in various matrices, atom probe tomography (APT) offers a unique combination of high analytical sensitivity coupled with high spatial resolution [1]. SIMS achieves its sensitivity by analyzing relatively unconstrained sample volumes, analyzed areas often greater than several hundred square microns. Square microns of material cannot be analyzed by APT and so it can never compete with SIMS for sensitivity at the micron scale; however, the situation is very different at the nanoscale—the regime of individual device volumes. Within this regime APT has high, uniform, quantitative chemical sensitivity with sub-nanometer spatial sensitivity.

Understanding the precision and accuracy of APT when applied to ion implanted dopant profiles is essential for general adoption by the semiconductor industry. Three-dimensional atom positions are determined using a simple point-projection methodology [2]. Adopting best practices within the constraints of this methodology is necessary to allow uniform and unbiased determination of atom positions and depth profiles. Although the ultimate sensitivity of APT is determined by counting statistics, it is well known that counting statistics alone do not fully account for accuracy limitations. The free parameters available within the reconstruction process are often dominant in terms of total observed error.

During this presentation, a number of examples will be shown of APT applied to the analysis of dopant distributions in relevant structures. The focus will be ion implanted structures with discussion of best practice approaches to minimize error and remove bias by the practitioner. Material structures include a series of NIST Standard Reference Material implants into silicon [3] and additional implants into GaN-based materials.

[1] T.F. Kelly and D.J. Larson, *Annual Reviews of Materials Research* 42 (2012) 1.

[2] P. Bas et al., *Surf. Sci.* 87/88 (1995) 298.

[3] R.R. Greenberg et al., *Radioanal. Nucl. Chem,* 245 (2000) 57.

4:40pm **PS+AP+SE-ThA8 Optical Emission Spectroscopy to Determine Plasma Parameters in an Oxygen Inductively Coupled Plasma**, ***Nathaniel Ly***, *J. Boffard, C.C. Lin, A.E. Wendt,* University of Wisconsin - Madison, *S. Radovanov, H. Persing, A. Likhanskii*, Applied Materials, Inc.

The success of ion implantation to precisely modify substrate properties requires control of the incident ion energies to achieve the desired depth of the implanted ions. Oxygen plasmas generally contain both O^+ and O_2^+ positive ions, and in plasma immersion ion implantation (PIII) of oxygen, the two will produce different concentration depth profiles due to their different energy/mass ratios. Predicting the overall profile thus requires knowledge of the relative fluxes of the two ion species. Motivated by the long term goal of a robust predictive model, here we combine experiment and numerical simulation to investigate the feasibility of using non-invasive optical emission spectroscopy (OES) to monitor plasma parameters in an oxygen inductively-coupled plasma. Initial experiments made use of a small admixture of argon with the oxygen to take advantage of established techniques involving argon OES. In addition to recording argon emissions, measurements of multiple O, O_2, O^+, and O_2^+ emission intensities were made as a function of pressure (1-30 mTorr) and power (500-2000 W). An emission model makes use of available electron impact excitation cross sections for argon and atomic and molecular oxygen to relate measured emission spectra to corresponding plasma parameters, including electron temperature and the dissociation fraction of the neutral oxygen. Data taken while as a function of the percentage of argon in the Ar/O_2 mixture showed that even a very small admixture of argon significantly affected the oxygen plasma properties, and more recent experiments have thus focused on oxygen OES in a pure oxygen plasma. The CRTRS 2D/3D plasma code self-consistently and semi-implicitly solves for ICP power deposition and uses Poisson's equation to solve for the electrostatic potential and dynamics of electrons and ions in the drift-diffusion approximation (or full momentum equations). The code also solves for the electron temperature, and generation and quenching of excited states as well as their dynamics. The experimental results are used in combination with simulation predictions to understand the dependence of plasma parameters, including the relative fluxes of O^+ and O_2^+, on the operating parameters.

The authors acknowledge support from NSF grant PHY-1068670.

5:00pm **PS+AP+SE-ThA9 Adhesion Improvement of Carbon Nitride Coatings on Steel Surfaces by Metal Ion Implantation using HiPIMS**, ***Konstantinos Bakoglidis***, *G. Greczynski, S. Schmidt, L. Hultman*, Linkoping University, Sweden

Carbon based thin films are materials with low friction and wear resistance. Deposition of C based thin films as coatings on steel substrates can enhance the tribological performance of steel surfaces. Adhesion of magnetron sputtered C based coatings on steel substrates is, however, often insufficient, leading to film delamination or flaking after the deposition. Adhesion is essential when such films are exploited in tribological applications and can be improved by using ion etching of the steel surface prior to film deposition. Several ion etching techniques are used, among them metal ion etching, for ion implantation in order to prepare the steel surface for the C film deposition. Moreover, high power impulse magnetron sputtering (HiPIMS) offers high metal ionization conditions and effectively enhances ion implantation into the steel subsurface. In this study, we used four different metal targets, namely Al, Cr, Zr, W, in HiPIMS mode in Ar-based plasma with a pressure of 200 mPa, and under a negative applied bias voltage of 900 V, which was synchronized with the cathode pulse. All targets were operated with an energy per pulse of 15 J, with pulse width of 200 µs, an etching time of 30 s, while the frequency was set at 100 Hz. A carbon nitride (CN_x) thin film was deposited after each etching step, using a graphite target in DC mode, operated at 1400 W, in a N_2/Ar gas mixture with a ratio of 0.16, and at a temperature of 150 °C, while the pressure was kept constant at 400 mPa. In all cases except Zr, a thin metal interlayer was obtained, with thicknesses < 20 nm, while adhesion of CN_x films on steel surface was dramatically improved when W ions were used for the pre-treatment phase.

Authors Index

Bold page numbers indicate the presenter