Advanced Ion Microscopy Focus Topic
Room 203B - Session HI-WeA

Novel Beam Induced Material Engineering & Nano-Patterning

Moderators: Armin Gölzhäuser, University of Bielefeld, Germany, Olga Ovchinnikova, Oak Ridge National Laboratory

2:20pm **HI-WeA-1 Delving into the Finer Details of Helium FIBID**, ***Frances Allen**,* University of California, Berkeley **INVITED**

Focused ion beam induced deposition (FIBID) of gaseous precursors enables localized template-free additive lithography at the nanoscale and is used in a range of applications, such as circuit edit in semiconductor engineering and the prototyping of nanodevices. To date, the majority of FIBID has used the gallium focused ion beam generated by the long-established liquid-metal ion source. However, with the development of the atomically sharp gas field-ionization source (GFIS) and subsequent emergence of the Helium Ion Microscope, FIBID using focused helium ion beams is increasingly of interest. The enhanced spatial resolution of helium FIBID over gallium FIBID and ability to deposit insulators free from gallium contamination are key areas of benefit.

The internal structure, composition, and overall shape of FIBID nanostructures and the influence of the deposition parameters thereon provide clues as to the growth mechanisms involved. Ultimately, the goal is to use this information to facilitate tunable FIBID in order to obtain nanostructures with a specific set of properties for a given application. I will present insights gleaned from scanning transmission electron microscopy (STEM) analysis of helium-FIBID nanostructures, where x-ray energy-dispersive spectrometry (XEDS) and new methods in "4DSTEM" diffraction are applied to obtain elemental compositions and grain orientation maps at the nanoscale with high sensitivity. The results are compared with those obtained for neon FIBID (the neon beam also generated by the GFIS source) and benchmarked against results from gallium FIBID. Several unique applications of helium FIBID drawing on the particular characteristics of helium-FIBID nanostructures will be discussed.

3:00pm **HI-WeA-3 Anderson localization of Graphene by Helium Ion Irradiation**, ***Yuichi Naitou**, S Ogawa,* National Institute of Advanced Industrial Science and Technology (AIST), Japan **INVITED**

Graphene has been the subject of intensive research for its unique physical properties. Recently, tuning the electrical properties of graphene by irradiating it with an ion beam or exposing it to a reactive gas atmosphere has been of great interest[1][2]. The basic idea is to generate defects by using accelerated ion beam bombardment or reactive gas treatment and then to introduce localized states around the charge neutral point of graphene. Such localized states govern the transport properties of graphene, and highly defective graphene as a transition into a two-dimensional Anderson insulator is theoretically predicted[3].

Irradiation of a single-layer graphene (SLG) with accelerated helium ions (He^+) by helium ion microscopy (HIM) controllably generates defect distributions, which create a charge carrier scattering source within the SLG. We report direct experimental observation of metal-insulator transition in SLG on SiO_2/Si substrates induced by Anderson localization. This transition was investigated using scanning capacitance microscopy by monitoring the He^+ dose conditions on the SLG. The experimental data show that a defect density of more than ~1.2% induced Anderson localization. We also investigated the localization length by determining patterned placement of the defects and estimated the length to be several dozen nanometers—no fewer than 20 nm and no more than 50 nm. These findings provide valuable insight for direct-patterning and designing graphene-based nanostructures using HIM. Further detail will be presented[4][5].

References

[1] J.-H. Chen et al. Phys. Rev. Lett. 102, 146805 (2009).

[2] S. Nakaharai, S. Ogawa et al. ACS Nano 7, 5 694 (2013).

[3] A. Lherbier et al. Phys. Rev. B 86, 075402 (2012).

[4] Y. Naito and S. Ogawa, Appl. Phys. Lett. 106, 033103 (2015)

[5] Y. Naito and S, Ogawa, Appl. Phys. Lett.108, 171605 (2016)

4:20pm **HI-WeA-7 The Frontiers of Focused Ion Beam in Semiconductor Applications**, ***Shida Tan**,* Intel Corporation **INVITED**

The semiconductor performance scaling or "Moore's Law" has completely transformed the face of the planet and our daily life in the past half a century. This innovation trend continues through a combination of the transistor density scaling, heterogeneous integration, and architectural breakthroughs. These smaller critical device dimensions, thinner process layers, densely packed structures, complex device routing, and design architecture pose challenges to the focused ion beam (FIB) technology, which is used broadly in the entire product development cycle from the fabrication process to the final product debug and failure analysis. In this paper, we will talk about the unique advantages and applications of alternative ion beam in the areas of circuit edit, failure analysis, fault isolation, yield analysis, and mask repair. Trade-offs between various beam parameters to enable successful recipe implementation, challenges of the existing technologies, and the requirements for future instrumentation development will be discussed.

5:00pm **HI-WeA-9 2D Materials Under Ion Irradiation: In-situ Experiments and the Role of the Substrate**, ***Gregor Hlawacek**, S Kretschmer,* Helmholtz Zentrum Dresden-Rossendorf, Germany*; M Maslov,* Moscow Institute of Physics and Technology*; S Ghaderzadeh, M Ghorbani-Asl, A Krasheninnikov,* Helmholtz Zentrum Dresden-Rossendorf, Germany

Helium ion Microscopy (HIM) is frequently used for the fabrication of 2D nanostructures in graphene, MoS_2 and other materials. While some of the experiments are carried out with freestanding materials most of the work is done on supported material. While the defect production is understood for the former case, it is not fully understood in the latter setup. We used a combination of analytical potential molecular dynamics and Monte Carlo simulations to elucidate the role of the different damage channels, namely primary ions, backscattered atoms and sputtered substrate atoms.

Using this approach we looked at the defect production by helium and neon ions in MoS_2 and graphene supported by SiO_2 at typical energies used in HIM. We show that depending on ion species and energy defect production for supported 2D materials can be dominated by sputtered atoms from the support, rather than direct damage induced by the primary ion beam. We also evaluated the consequences of these additional damage mechanisms on the achievable lateral resolution for HIM based defect engineering and nano-fabrication in 2D materials. The obtained results agree well with experimental results obtained by in-situ and ex-situ characterization of defects in graphene and MoS_2.

5:20pm **HI-WeA-10 Sample Heating Effects from Light Ions in Thin Films**, ***John A. Notte**, B Lewis,* Carl Zeiss Microscopy, LLC

The term "FIB Renaissance" has been applied to the recent period of ion source development which has brought forth many new species suitable for focused ion beam (FIB) instruments. Several of the new species are relatively light ions, including hydrogen, helium, lithium, and neon, which are appreciably lighter than the prevailing gallium FIB – by a factor of 3 or more. At the conventional energies (5 to 30 keV) these ions species interact with the sample differently, and warrant a reconsideration of the established understanding which is largely founded on the traditional gallium FIB.

The most marked distinction of these light ions is the ratio of electronic stopping power compared to nuclear stopping power. For example, for a 30 keV helium ion, the nuclear stopping power can be a decade lower than its electronic stopping power. While for 30 keV gallium, the nuclear stopping power is a decade higher than the electronic stopping power. Consequential to this, near the surface the light ions remain relatively collimated because $M_{ion} >> M_{elec}$, making angular deflections necessarily small. As the light ions gradually penetrate deeper, they lose their energy, and the electronic stopping power is correspondingly reduced until the nuclear stopping power dominates. Here, large angular deflections become dominant, and the majority of the lattice damage takes place at these greater depths for light ions. For the special case of thin films, nuclear stopping might never become predominant for light ions.

The heat transfer mechanisms are even more drastically different when comparing light ions to heavier ions. First, by virtue of their large penetration depth, the light ions have a larger volume in which their energy is dissipated – reducing the corresponding temperature rise. But more significantly, the light ions lose most of their energy through excitations to the electrons. These excited electrons have characteristic mean free paths which can be relatively long, providing an effective pathway for energy transfer to a much larger volume. Whereas for nuclear stopping power, the ion's energy is transferred to the lattice much more locally. And since nuclear stopping is predominant for heavy ions, the energy is necessarily deposited locally, giving rise to appreciably higher temperature. Further, for the special case of thin films, the temperature rise from light ions is further reduced. Lastly, a special case of low beam currents is considered, where the time interval between ion arrivals may sometimes be longer than the time scale for thermal relaxation. This gives rise to non-overlapping temperature spikes which can be independent of probe current.

5:40pm **HI-WeA-11 Helium Ion Direct Write Patterning of Superconducting Electronics***, **Shane Cybart**, E Cho, H Li,* UC Riverside*; Y Naitou, S Ogawa,* National Institute of Advanced Industrial Science and Technology (AIST), Japan

We report the fabrication of nanoscale Josephson junctions in 25 nm thick YBa2Cu3O7 thin films. Our approach utilizes a finely focused gas field ion source from a helium ion microscope to directly modify the material on the nanometer scale to convert irradiated regions of the film into insulators. In this manner, the film remains intact and no material is milled or removed. We will present results of how the critical dimension beam affects the electrical properties. Furthermore we reflect on the potential of this method for future device applications in superconducting computing.

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