Advanced Ion Microscopy and Ion Beam Nano-engineering Focus Topic
Room On Demand - Session HI-Contributed On Demand
Advanced Ion Microscopy & Nano-Engineering Contributed On Demand Session

HI-Contributed On Demand-1 Applications of the Cesium Low Temperature Ion Source, ***Adam Steele,*** *A. Schwarzkopf,* zeroK NanoTech Corporation*; B. Knuffman,* zeroK NanoTech Corporation

We present the latest results from FIB and FIB+SIMS systems featuring the Cs^+ Low Temperature Ion Source (LoTIS). When compared with other ion sources LoTIS can deliver very small spot sizes, high sputter rates, high yields of secondary ions, and a wide range of beam currents from pA to many nA.

We will review applications of LoTIS tested on a single beam FIB system. These include high resolution imaging, long depth-of-focus imaging, successful circuit edit operations on 10 nm node integrated circuits, high-precision machining of gold, and demonstration of the high grain-visibility imaging in copper and steel offered by LoTIS.

Previously we reported spot sizes as small as (2.1 ± 0.2) nm (one standard deviation) are observed with a 10 keV, 1.0 pA beam. Brightness values as high as (2.4 ± 0.1) × 107 A m-2 sr-1 eV-1 are observed near 8 pA [1]. The measured peak brightness is over 24 times higher than the highest brightness observed in a Ga liquid metal ion source (LMIS). This system has generated beam exceeding 11 nA. LoTIS is composed of a several discrete stages that collect, compress, cool and finally photoionize a cesium atomic beam [2].

The talk will conclude by reviewing our progress in the construction of a high resolution FIB/SIMS hybrid system called SIMS:ZERO; this system is being built in collaboration with the Luxembourg Institute of Science and Technology (LIST). SIMS:ZERO will be capable of high-resolution FIB operations while also providing a new material analysis information channel through the application of Secondary Ion Mass Spectrometry (SIMS). For many target materials Cs+ will generate orders or magnitude more secondary ions than other ion ions. In addition, LoTIS is can provide over 100x more current into a given spot than alternative Cs^+ ion sources.

[1] A. V. Steele, A. Schwarzkopf, J. J. McClelland, and B. Knuffman. Nano Futures. 1, 015005 (2017).[2] B Knuffman, AV Steele, and JJ McClelland. J. Appl. Phys. 114, 4 (2013).

HI-Contributed On Demand-7 Focused Nanoscale Machining via the Gas Field Ion Microscope with Laser and Reactive Ion Assist: Joint Experimental and Simulation Investigations, ***Jack Lasseter,*** *P. Rack,* University of Tennessee Knoxville

Focused ion beams utilizing light atoms like helium and neon are able to be used in materials processing providing nanoscale manipulation from milling, to reactive ion etching, to 3D nanomaterials deposition. However very light atoms like helium require high doses for milling applications and thus can suffer sub-surface implantation effects like substrate damage through bubbling, so nanofabrication can require extra care. Thus, reactive ion and laser-assisted focused ion beam techniques can be used to enhance the sputtering and thus minimize sub-surface damage. To emulate focused ion beam nanomachining, we have developed the EnvizION simulation code, which at its core uses SRIM/TRIM statistical descriptions of ion-solid interactions to model 3D substrates through a voxelized substrate.

The nanoscale resolution and ability to image insulating samples provides ion microscopes formidable nanofabrication abilities. In this presentation we will overview our groups recent experimental work in gas field ion nanomachining and complement the experiments with various EnvizION simulations. Applications include defect generation in two-dimensional materials such as transition metal dichalcogenides, gas assisted deposition to print 3D PtC structures from a $(CH_3)_3Pt(C_pCH_3)$ gas precursor, and laser + XeF_2 gas pulsing methods to enhance the material removal rate of WSe_2 and SiO_2. The laser assisted XeF_2 has been shown to enhance the etch yield by 9x relative to a pure helium sputtering process. Finally, we have incorporated reactive gas etching in the EnvizION simulation and have performed an exhaustive comparison with both Ga^+ and Ne^+ milling and XeF_2 reactive etching. Since the subsurface damage is a function of the dose these types of enhancements are stepping stones to overcome damage related roadblocks.

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HI-Contributed On Demand-10 Imaging of SARS-CoV-2 infected Vero E6 Cells by Helium Ion Microscopy, ***Natalie Frese,*** Bielefeld University, Germany*; P. Schmerer,* Justus-Liebig-University Giessen, Germany*; M. Wortmann,* Bielefeld University of Applied Sciences, Germany*; M. Schürmann ,* Bielefeld University, Germany*; M. König,* Justus-Liebig-University Giessen, Germany*; M. Westphal,* Bielefeld University, Germany*; F. Weber,* Justus-Liebig-University Giessen, Germany*; H. Sudhoff, A. Gölzhäuser,* Bielefeld University, Germany

Helium ion microscopy (HIM) enables the visualization of biological samples such as cellular structures, virus particles, and microbial interactions with sub-nanometer resolution, large depth of field, and high surface sensitivity. The charge compensation capability of the HIM allows imaging of insulating biological samples without conductive coatings. In this contribution, the first HIM images of uncoated SARS-CoV-2 infected Vero E6 cells are presented [1]. Several areas of interactions between cells and virus particles, as well as among virus particles, were imaged. The images show the three-dimensional appearance of SARS-CoV-2 on the surface of Vero E6 cells and demonstrate the potential of the HIM in bioimaging, especially for the imaging of interactions between viruses and their host organisms.

[1]N. Frese et al., *Beilstein J. Nanotechnol.* 12(1), 172-179 (2021).

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Advanced Ion Microscopy & Nano-Engineering Invited On Demand Session

HI-Invited On Demand-1 Nanoscale Vortex Pinning Structures in High-Temperature Superconductors Created in a Helium Ion Microscope, ***Wolfgang Lang,*** *B. Aichner,* University of Vienna, Austria*; M. Karrer, K. Wurster,* Universität Tübingen, Germany*; V. Misko,* Universiteit Antwerpen, Belgium*; K. Mletschnig,* University of Vienna, Austria*; M. Dosmailov,* Al-Farabi Kazakh National University, Kazakhstan*; J. Pedarnig,* University of Linz, Austria*; F. Nori,* RIKEN, Japan*; R. Kleiner, E. Goldobin, D. Koelle,* Universität Tübingen, Germany **INVITED**

The focused beam of a helium ion microscope is used to fabricate ultradense patterns of superconducting/insulating domains in thin films of the prototypical cuprate superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) with unprecedented lateral resolution down to 40 nm. Simulations of the He^+ ion-target interactions [1] reveal 3-dimensional defect landscapes and allow one to determine the distribution of local critical temperatures in the material. The simulations anticipate that well-defined patterns of non-superconducting material in the superconducting matrix can be created with low blurring by focused 30 keV He^+ ion irradiation.

In such engineered defect patterns, the behavior of magnetic flux quanta, called Abrikosov vortices or fluxons, is investigated in view of emerging superconducting electronics, known as fluxonics. As an initial step along this route vortex commensurability effects are investigated that result from trapping fluxons at the engineered defects [2]. We report on the observation of novel commensurability effects in ultradense kagomé-like pinning patterns, where a competition between vortex pinning and the elastic energy of the distorted vortex lattice leads to unusual matching effects, as revealed by transport measurements and molecular-dynamic simulations [3]. Other intriguing observations in these ultradense superconducting patterns like vortex ratchet effects will be also discussed.

[1] K. L. Mletschnig and W. Lang, Microelectron. Eng. **215**, 110982 (2019).

[2]B. Aichner, K. L. Mletschnig, B. Müller, M. Karrer, M. Dosmailov, J. D. Pedarnig, R. Kleiner, D. Koelle, and W. Lang, Low Temp. Phys. **46**, 331 (2020).

[3]B. Aichner, B. Müller, M. Karrer, V. Misko, F. Limberger, K. L. Mletschnig, M. Dosmailov, J. D. Pedarnig, F. Nori, R. Kleiner, D. Koelle, and W. Lang, ACS Appl. Nanomater., **2**, 5108 (2019).

HI-Invited On Demand-7 Cluster Ion Beams: A New Tool for Characterization and Processing of Organic and Biological Materials*, Jiro Matsuo,* Quantum Science and Engineering Center, Kyoto University, Japan **INVITED**

Ion beams have been utilized for various applications, such as implantation, sputtering, etching and thin film formation for inorganic materials. However, it is quite difficult to apply ion beam technique for organic materials, because organic materials are easily decomposed with ion bombardments. This is due to the fact that bonding energy in organic molecule is much lower than a kinetic energy of ions. Recently, organic materials, such as functional-polymer, organic semiconductors and biological materials, are of interest in not only fundamental research but also many industrial applications. It has been demonstrated that large cluster ion beams have a great potential to sputter organic molecules without any residual damage on the surface, because cluster ion beams are equivalently low energy ion beams. Energy of cluster ion is shared with the constituent atoms in the cluster ion. For instance, when large Ar cluster ions with the cluster size of 1000 are accelerated with 10keV, each constituent atom has only 10eV/atom, which is comparable for binding energy of organic molecules. Therefore, cluster ion beams are now widely utilized for organic depth profile measurements in XPS or SIMS. More than 70% of those surface analysis system is delivered with GCIB source. It has been confirmed that no or very little damage is introduced on organic surfaces after large cluster ion bombardments. However, there is no report on molecular structure of sputtered species from organic materials. Sputtered molecules from PMMA were captured on Si wafers and measured with XPS technique. C 1s core level spectrum was almost identical to that of pristine PMMA. This measurement reveals that most of the carbon atoms have very similar chemical structures, but it is very difficult to measure molecular structures. We have also developed a finely focused large cluster ion beam (~1mm) for the primary ion beam for use in SIMS [1] and combined it with mass spectrometers of the quadrupole time-of-flight mass spectrometry (Q-TOF) type without pulsing primary ions. This mass spectrometer is equipped with MS/MS capability and allows to determine the structure of the secondary ion by using the collision-induced dissociation (CID) technique. This new system allows us to characterize 3D distribution of organic molecules.Fundamental phenomena of cluster ion collision with organic molecules will be discussed in conjunction with possible applications.

[1] J. Matsuo, S. Torii, K. Yamauchi, K. Wakamoto, M. Kusakari, S. Nakagawa, M. Fujii, T. Aoki, and T. Seki, *Appl. Phys. Express,* ***7*** (2014), 056602

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