Advanced Ion Microscopy Focus Topic
Room: 7 & 8 - Session HI-WeA

Emerging Ion Sources and Optics
Moderator: John A. Notte, Carl Zeiss Microscopy, LLC

2:20pm **HI-WeA1 COLDFIB – The New FIB Source from Laser Cooled Atoms**, *E. Verzeroli, **Anne Delobbe**, M. Viteau,* Orsay Physics, France*, D. Comparat,* CNRS Lac Orsay, France*, A. Houel, M. Reveillard*, Orsay Physics, France **INVITED**

Charged particle beams of controlled energy and strong focusing are widely used tools in industry and science. Focused Ion Beam (FIB) column combine with a Scanning Electron Microscope (SEM) provide full control of nanofabrication or nanolithography processes. Ion energy can be varied typically in the 1–30KeV range, with an energy-dependent resolution attaining the nanometer range. State-of-the-art FIBs commercially available are based mainly on plasma, liquid metal tip or helium ion sources for large, intermediate, and low currents, respectively. Despite the very high technological level of the available machines, research of new ion sources allowing even higher resolution and a wider choice of atomic or molecular ions for new and demanding application is very active.

As an example, the world of electronic components evolves regularly towards the miniaturization by integrating a number of transistors more and more important. The dimensions being smaller and smaller (technology 10 nm, 7 nm even 5 nm), nowadays the instruments of analysis used, like the conventional FIB, reach their limit. Thus it’s necessary to realize a technological breakthrough to be able to observe, analyze and modify components and structures on the scale of the nanometer.

Our new system, COLDFIB, wants to take up this challenge of the nanomanufacturing by the coupling of two high technologies: the laser cooling of atoms, and manipulation of charged particles.

Very innovative, this industrial solution, based on a source of ions obtained from atoms laser cooled and ionized, will allow realizing ions beam in the unequalled performances, to reach engraving’s sizes of some nanometers. This new technology offers a resolution, for example at 5KeV, 10 times better than the LMIS one, and reaches the nanometer at 30keV *(Figure 1)*.

We’ll present in this talk the integration on the SEM-FIB TESCAN instrument. In addition to the experimental[1] part and performances[2] will also show some first applications.

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[1] L. Kime, et al., *High-flux monochromatic ion and electron beams based on laser-cooled atoms*, Phys. Rev. A 88, 033424 (2013)

[2] M. Viteau, et al., *Ion microscopy based on laser-cooled cesium atoms*, Ultramicroscopy (2016)

3:00pm **HI-WeA3 FIB Platform Employing a Low-Temperature Ion Source**, ***Adam Steele**, A. Schwarzkopf*, zeroK NanoTech*, J.J. McClelland,* National Institute of Standards and Technology*, B. Knuffman*, zeroK NanoTech

We present a demonstration of a new high-performance ion source retrofitted to a commercial FIB platform. 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 $(2.4 \pm 0.1) \times 10^7$ 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); the spot size obtained by operating our source at 10keV is significantly smaller than the spot size achievable with the replaced LMIS operating at 40 keV.

The FIB platform utilizes a Low Temperature Ion Source (LoTIS). As previously described [2], this source is composed of a several discrete stages that collect, compress, cool and finally photoionize a cesium atomic beam. High brightness and small spot sizes are achieved owing to the extremely low (10 uK) temperatures that may be achieved in the neutral atomic beam prior to photoionization. The atomic beam transmits over 5×10^{10} atoms s^{-1}, which would be equivalent to an ion beam with over 8 nA if ionized completely; extraction of currents up to 5 nA have been demonstrated to date.

We will present a description of the Cs^+ LoTIS-FIB system, together with an examination of the brightness and spot size measurement methodology at beam currents up to a nanoampere. Images acquired using the system will also be shown. Finally, we will describe outcomes of some preliminary milling, gas assisted etching and deposition experiments performed with the system.

[1] A. V. Steele, A. Schwarzkopf, J. J. McClelland, and B. Knuffman. *Nano Futures*. **1**, 015XXX (2017). (to be published 5/2017)

[2] B. Knuffman, A. V. Steele, and J. J. McClelland. *J. Appl. Phys.* **114**, 044303 (2013).

3:20pm **HI-WeA4 Focused Cs Ion Beam Nanomachining and Material Interaction Characterization for Semiconductor Applications**, ***Richard Livengood**, R. Hallstein, S. Tan,* Intel Corporation, USA*, Y. Greenzweig, Y. Drezner, A. Raveh,* Intel Corporation, Israel*, A.V. Steele, B. Knuffman, A. Schwarzkopf,* zeroK NanoTech, USA

Focused ion beam Nanomachining is used extensively in semiconductor materials and circuit analysis applications. Applications range from using ion beams for large area machining for de-process sample for metrology and defect analysis, to high precision nanomachining to access device circuits [1,2]. There have been many different focused ion beam technologies developed and refined over the last 30 years to perform this type of machining. The two primary focused beam-source technologies used today are: Gallium Liquid Metal Ion source (LMIS) for micro and nanomachining applications [3,4]; and 2) Xenon plasma-cusp ion sources used for bulk material micro-machining in packages interconnects, TSV's, and backend metal layers [5,6]. More recently, the neon and nitrogen (N2) gas field ion sources (GFIS) have also been introduced to enable very small, high precession Nanomachining for circuit rewiring and mask defect repairs respectively [7,8]. Another emerging ion beam / source technology are cold beams (base on ionization of atoms cooled to sub kelvin temperatures, which gives them very low energy spread) [9]. Two such emerging sources are cesium based cold beam sources under development by ZeroK Nanotech Inc. and TOH (Tescan Orsay-Physics Holdings) [10,11].

As part of Intel's due diligence to identify break through ion beam technologies to keep pace with semiconductor scaling requirements and help identify novel analytical applications, Intel has recently been analyzing the attributes of cesium for semiconductor applications [12]. In this paper, we will discuss the attribute requirements for various semiconductor applications and publish early cesium beam machining performance attributes - based on joint characterization experiments performed by Intel and ZeroK Nanotech on cesium LoTIS focused ion beam using ZeroK's proof of concept test platform. Analysis will include preliminary characterization results for material sputter rates, beam induced etching, and other Nanomachining attributes.

4:20pm **HI-WeA7 Spectroscopy in the Focused Ion Beam**, ***Robert Hull***, Rensselaer Polytechnic Institute*, H. Parvaneh,* Global Foundries **INVITED**

We review spectroscopic methods in the focused ion beam (FIB), and introduce the coupled Auger Electron Spectroscopy (AES) – FIB technique. While FIB tomography has become a widely-used method for exploring 3D structure of materials over length scales ranging from tens of nm to tens of µm, complementary high resolution and high sensitivity spectroscopic methods are lacking. Secondary ion mass spectroscopy (SIMS) methods are limited by low ionization yields using conventional Ga^+ liquid metal ion source (LMIS) species and/or by low detector transmission factors. The anticipated advantage of coupling AES to the FIB is that Auger electron yields per incident ion can be in the few percent range depending on the experimental conditions, improving on Ga^+ ionization yields by several orders of magnitude for many elements. We have integrated an Orsay Physics Cobra mass-selecting FIB column into a PHI VersaProbe X-Ray Photoelectron Spectroscopy (XPS) system, successfully aligning the focal points of the FIB and of the detector/analyzer optics with the necessary precision in 3D dimensions. Using primary ions with different masses (e.g. from an Au-Si alloy source), we can control the relative proportions of the Auger transitions from the atoms of the target sample rather than from backscattered/implanted atoms from the primary beam. We have studied a set of elemental targets, with strong Auger peaks observed from each. For some elements (e.g. Mg, Al and Si), additional extremely sharp peaks are observed, superimposed on the standard Auger peaks. These are due to Auger emission from atoms that have been sputtered from the surface before the inner shell vacancy is filled. The occurrence of these free atom peaks in a subset of the samples can be understood in terms of the substantially longer vacancy state lifetimes in the core levels of some elements, allowing the target atom to escape from the surface field before Auger decay happens. For example, we observe average Auger yields of 0.06 for Cr and 0.09 for Al per incident 60 keV Si_2^+ ion. Coupled with the estimated transmission factors and solid angular detection range of the XPS hemispherical analyser employed, this translates into detection of atomic concentrations of order 0.1-1.0 % within a $(50\ nm)^3$ voxel. These figures of merit will be compared (favorably) to other spectroscopic methods available in the FIB.

5:00pm **HI-WeA9 Spark-discharge Coupled Laser Multicharged Ion Implantation and Deposition System**, ***Md Haider Shaim***, *M. Rahman, O. Balki, H.E. Elsayed-Ali*, Old Dominion University

Multicharged ions are generated by a Nd:YAG laser (λ = 1064 nm, τ = 7 ns, pulse energy $\leq$175 mJ) ablation of aluminum and boron targets in an ultrahigh vacuum. Time-of-flight and electrostatic retarding field ion energy analyzers are used to detect the laser-generated ions. Spark discharge coupling to the laser ion source enhances ion generation along with generating higher charge states than observed with the laser source alone. The spark discharge electrodes are located in front of the target and is triggered by the laser plasma. For an Al target with the laser source alone, the total ion charge delivered to a Faraday cup located 1.4 m away from the source is 1.0 nC with charge state up to Al^{3+}. When the spark amplification stage is used (0.1 μF capacitor charged to 5.0 kV), the total charge increases by a factor of ∼9 with up to Al^{6+} observed. The spark discharge increases the multicharged ion generation without increasing target ablation, which solely results from the laser pulse. An electrostatic cylindrical ion deflector is used for analysis and selection of charges with a specific energy-to-charge ratio. A three-electrode cylindrical einzel lens is used to focus the ion beam. A minimum ion beam diameter of ~1.5 mm was obtained. A high-voltage pulse applied to a set of two parallel deflecting plates is used for the pickup of ions with different charge states according to their time-of-flight. Fully stripped B ions with 150 eV per charge are obtained with the laser alone. These ions are used for shallow implantation without further acceleration. Al multicharged ion generation from femtosecond laser (λ = 800 nm, τ = 100 fs, pulse energy $\leq$1 mJ) ablation is also studied. Production of Al ions up to Al^{6+} is observed with the laser alone. Compared to nanosecond laser ablation, multicharged ion generation by femtosecond laser ablation require significantly lower laser fluence and generates higher charge states and more energetic ions.

Authors Index

Bold page numbers indicate the presenter

— B —

Balki, O.: HI-WeA9, 2

— C —

Comparat, D.: HI-WeA1, 1

— D —

Delobbe, A.: HI-WeA1, **1**

Drezner, Y.: HI-WeA4, 1

— E —

Elsayed-Ali, H.E.: HI-WeA9, 2

— G —

Greenzweig, Y.: HI-WeA4, 1

— H —

Hallstein, R.: HI-WeA4, 1

Houel, A.: HI-WeA1, 1

Hull, R.: HI-WeA7, **1**

— K —

Knuffman, B.: HI-WeA3, 1; HI-WeA4, 1

— L —

Livengood, R.H.: HI-WeA4, **1**

— M —

McClelland, J.J.: HI-WeA3, 1

— P —

Parvaneh, H.: HI-WeA7, 1

— R —

Rahman, M.: HI-WeA9, 2

Raveh, A.: HI-WeA4, 1

Reveillard, M.: HI-WeA1, 1

— S —

Schwarzkopf, A.: HI-WeA3, 1; HI-WeA4, 1

Shaim, M.: HI-WeA9, **2**

Steele, A.V.: HI-WeA3, **1**; HI-WeA4, 1

— T —

Tan, S.: HI-WeA4, 1

— V —

Verzeroli, E.: HI-WeA1, 1

Viteau, M.: HI-WeA1, 1