

Thursday Afternoon, November 13, 2014

Helium Ion Microscopy Focus Topic

Room: 316 - Session HI+2D+AS+MC-ThA

Nanoengineering with Helium Ion Beams

Moderator: Armin Götzhäuser, University of Bielefeld, Germany, David C. Joy, University of Tennessee, Oak Ridge National Laboratory

2:20pm **HI+2D+AS+MC-ThA1 Helium Ion Microscopy (HIM) Technology for Imaging, Characterization, and nano-Fabrication for nano-Device Materials and Structures, Shinichi Ogawa, NeRI, AIST, Japan**
INVITED

Several unique applications of a helium ion microscopy (HIM) technology have been studied. In comparison with electron, helium ion has larger cross section, and it realized HIM observation with less current because of higher efficiency of secondary electron generation with maximum distribution energy of 1 eV [1], a few eV in a SEM case, for imaging, which results in less power implant (less thermal damage input) into samples. Utilizing these features, a low dielectric constant material pattern of 70 nm line with less deformation (thermal damage) and a Cu metal line underneath a 130 nm dielectric of band gap of a few eV were imaged [2]. Luminescence from a SiO₂ sample was detected at imaging conditions [3], in which no damage was observed by a transmission electron microscopy (TEM) - electron energy loss spectroscopy method [4]. As one of nano-fabrication applications, we found that a helium ion irradiation using the HIM functionalizes a gate control of carrier conduction in a single-layer graphene at an appropriate amount of helium ion dose to graphene which enable gate bias control of current with an on-off ratio of two orders of magnitude at room temperature [5], [6]. A few nm diameter tungsten particles were deposited onto a TEM sample under the helium ion beam irradiation in W(CO)₆ gas atmosphere with high special resolution accuracy, which realized precise electron tomography and re-construction [7], and tungsten pillars of a few um height with 40 nm diameter were formed with a straight hole of a few nm diameter through a center of the pillars [8]. The research on graphene material is granted by JSPS through FIRST Program initiated by CSTP.

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3:00pm **HI+2D+AS+MC-ThA3 MEMS Temperature Controlled Sample Stage for the Helium Ion Microscope, Jose Portoles, P.J. Cumpson, Newcastle University, UK**

The Helium microscope allows the imaging of samples with magnifications beyond those of electron microscopes with the added advantages of directly imaging insulators without being so critically dependent on a need to conductive coating the samples. This facilitates the imaging of for instance organic structures without the need of surface modification. The large depth of focus allows simultaneously focusing details of the sample at different depths. When using a temperature controlled stage this allows the samples to stay focused as thermal expansion produces vertical displacements of the sample surface, however due to the large magnifications in-plane thermal expansions are still an issue. We have investigated a solution based on a thermally actuated X-Y MEMS stage by exploiting the ability of MEMS actuators to provide smooth electronic control of lateral displacements in the micron range in order to compensate for lateral thermal expansion at the point of observation. The difficulties involved in producing relatively large out of plane displacements with a MEMS device can be neglected due to the large instrumental depth of focus. The device we present has been fabricated using a "silicon on insulator" (SOI) MEMS process, and can be driven at low voltages and currents using a standard vacuum feedthrough to the instrument's analysis chamber and compensate lateral thermal expansion in order to keep any spot on a small specimen in the field of view at high magnifications. The small size of the heating stage makes it rapid in its thermal response.

3:20pm **HI+2D+AS+MC-ThA4 Monte Carlo Simulations of Focused Neon Ion Beam Induced Sputtering of Copper, Rajendra Timilsina, P.D. Rack, The University of Tennessee Knoxville, S. Tan, R.H. Livengood, Intel Corporation**

A Monte Carlo simulation has been developed to model the physical sputtering and nanoscale morphology evolution to emulate nanomachining with the Gas Field Ion Microscope. In this presentation, we will present experimental and simulation results of copper vias milled by a focused neon ion beam. Neon beams with a beam energy of 20 keV and a Gaussian beam profile with full-width-at-half-maximum of 1 nm were simulated to elucidate the nanostructure evolution during the physical sputtering of high aspect ratio features. In this presentation we will overview our simulation attributes which includes an evolving real-time sputtered via profile considering both the sputtered and re-deposited material. The sputter yield and sputter profile vary with the ion species and beam parameters and are related to the distribution of the nuclear energy loss in the material. We will also illustrate how the effective sputter yield is aspect-ratio dependent due to the change in the effective escape angle of the sputtered species. Quantitative information such as the sputtering yields, dose dependent aspect ratios and resolution-limiting effects will be discussed. Furthermore, we will show that the calculated nuclear energy loss and implant concentration ahead of the sputtering front correlates to observed damage revealed by transmission electron microscopy.

4:00pm **HI+2D+AS+MC-ThA6 Circuit Edit Nanomachining Study using Ne+ & He+ Focused Ion Beam, Richard Livengood, S. Tan, Intel Corporation**
INVITED

FIB nanomachining has been used extensively for over 20 years for the purpose of rewiring integrated circuits to validate design changes, isolate process faults, and generate engineering samples. During this time frame, the minimum feature size of an IC (Moore's Law) has scaled from 500nm to 14nm (36X) compared with ~6X scaling of Ga+ FIB. As a result FIB nanomachining capabilities have been steadily eroding over the last several generations, limiting the types of circuit modifications that can be successfully completed. There are however, several promising new ion beam scaling R&D initiatives that provide hope of enabling further nanomachining scaling into the sub 10nm process node.

One such technology is GFIS (gas field ion source) technology. He+ GFIS based FIBs have been successfully used to image with sub 0.5nm resolution and nanomachine sub 10 nm structure in Au, Graphene, and other thin film structures.[1, 2, 3] More recently He+ and Ne+ GFIS sputtering properties have been studied for nanomachining in bulk semiconductor films.[4] In this paper, we will show our latest results on GFIS FIB GAE (gas assisted etch) nanomachining and IBID properties and electrical invasiveness impact.

References

- [1] J. Notte, M. Rahman, L. Farkas, S. Tan, and R. Livengood, *Scanning* 33, 1 (2011).
- [2] D. S. Pickard, V. Viswanathan, M. Bosman, J. Dorfmueller, H. Giessen, Z. Ai, H. Hao, M. Mahmoudi, Yue Wang and Chao Fang, *Invited talk, EIBPN-HIM Session* (2012)
- [3] V. Sidorkin, E. v. Veldhoven, E. v der Drift, P. Alkemade, H. Salemink, D. Mass, *J. Vac. Sci. Technol. B* 27 (4) (2009)
- [4] S. Tan, R. Livengood, D. Shima, P. Hack, R. Hallstein, J. Notte, and S. McVey, *JVST B*, 29 (6), 06F604 (2011).

4:40pm **HI+2D+AS+MC-ThA8 Evaluation of EUV Resist Performance below 20-nm CD using Helium Ion Lithography, D.J. Maas, TNO Technical Sciences, Netherlands, Nima Kalhor, TU Delft, Netherlands, W. Mulckhuyse, E. van Veldhoven, TNO Technical Sciences, Netherlands, A. van Langen-Suurling, P.F.A. Alkemade, TU Delft, Netherlands, S. Wuister, R. Hoefnagels, C. Verspaget, J. Meessen, T. Fliervoet, ASML, Netherlands**
For the introduction of EUV lithography, development of high performance EUV resists is of key importance. This development involves studies into sensitivity, resolving power and pattern uniformity. We have used a sub-nanometer-sized 30 keV helium ion beam to expose chemically amplified (CAR) EUV resists.

There are remarkable similarities in the response of resists to He⁺ ions and EUV photons. Both primary particle beams traverse the resist and meanwhile interact with the target atoms. The low backscattering of the He⁺ ions results in ultra-low proximity effects, which is similar to EUV exposure. Absorption of an EUV photon creates a high-energy electron that relaxes by the excitation of Secondary Electrons (SEs). A collision of a 20-30 keV helium ion with a target atom directly releases low-energy SEs.

Each ion scatters several times in the resist layer, thus enabling resist exposures at very low doses per CH. The energy spectra of SEs generated by EUV and He⁺ are remarkably alike. These SEs, in turn, activate the resist.

In this paper we show 30 keV He⁺ ions exposures of contact holes and lines with a CD of 8 – 30 nm at 20 nm half-pitch in a chemically amplified EUV resist. We will demonstrate the potential of using He⁺ ion lithography [1,2] in the study of EUV resists.

[1] V. Sidorkin et al., *Sub-10-nm nanolithography with a scanning helium beam*, J. Vac. Sci. Technol. B **27**, L18 (2009)

[2] D. Maas et al., *Evaluation of EUV resist performance below 20nm CD using helium ion lithography*, SPIE Proc. **9048**, 90482Z (2014)

5:00pm **HI+2D+AS+MC-ThA9 Helium Ion Beam Lithography for Nanoscale Patterning**, X. Shi, University of Southampton, UK, D.M. Bagnall, University of New South Wales, UK, **Stuart Boden**, University of Southampton, UK

Electron beam lithography (EBL), the modification of thin films of resist by a focused beam of electrons to create a pattern that is subsequently transferred into the substrate, is a key technology in the development of nanoscale electronic devices. However, with the demand for ever smaller features and pattern dimensions, new lithographic techniques are required to extend beyond existing limits of EBL. One such emerging technology is helium ion beam lithography (HIBL), driven by the development of the helium ion microscope, a tool capable of producing a high intensity beam of helium ions focused to a sub-nanometer spot [1]. Preliminary studies on HIBL using typical EBL resist materials such as PMMA and HSQ have shown that HIBL has several advantages over EBL, including a smaller spot size (potentially leading to higher resolution patterning) and a decrease in the exposure dose required and so the potential for faster pattern definition and therefore higher throughput. Furthermore, proximity effects, which are caused by beam scattering leading to inadvertent exposure of surrounding material, and are problematic when producing high density patterns in EBL, are massively reduced in HIBL [2], [3].

Here, the latest results from an experimental investigation into the HIBL technique will be presented. Areas of PMMA films of various thicknesses are exposed to different helium ion doses. After subsequent development in MIBK/IPA, atomic force microscopy is used to measure residual layer thickness in order to generate exposure response curves for different initial thicknesses of resist. High sensitivity is confirmed with full exposure of 50 nm thick layers achieved with a helium ion dose of only ~2 $\mu\text{C}/\text{cm}^2$. Experiments to characterise minimum feature size and proximity effects are currently underway. The use of other high resolution resists will also be investigated with the aim of providing a thorough assessment of the capabilities and limitations of this emerging nano-patterning technique.

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[2] D. Winston, B. M. Cord, B. Ming, D. C. Bell, W. F. DiNatale, L. A. Stern, A. E. Vladar, M. T. Postek, M. K. Mondol, J. K. W. Yang, and K. K. Berggren, "Scanning-helium-ion-beam lithography with hydrogen silsesquioxane resist," *J. Vac. Sci. Technol. B.*, vol. 27, no. 6, pp. 2702–2706, 2009.

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5:20pm **HI+2D+AS+MC-ThA10 Sub-100nm Nanofabrication using Helium and Neon Ion Beams**, **James Sagar**, C. Nash, N. Braz, T. Wootton, M.J.L. Sourribes, T.-T. Nguyen, R.B. Jackman, P.A. Warburton, London Centre for Nanotechnology, UK

Sub-100nm Nanofabrication using Helium and Neon Ion Beams

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Using a Zeiss Orion NanoFab we have created sub-100nm devices for experiments in quantum electronics and nanophotonics. The Orion NanoFab has the ability form an ion beam with either helium or neon gas. This makes the Nanofab a much more versatile instrument for nanofabrication since large area mills can be performed using Ne without the need for a Ga FIB column. The use of a Ne gas field ion source (GFIS) in the Orion NanoFab allows fabrication of sub-100nm devices on timescales comparable to that of conventional liquid Ga FIB but with considerably enhanced fidelity due to an increased sputter yield (ten times greater than that of He) whilst retaining a small probe size ($\leq 5\text{nm}$). Using a Ne ion beam we have

fabricated two kinds of nanoscale superconducting devices: a superconducting nanowire based on a compound low-T_C superconductor; and an array of nanoscale Josephson junctions based on a compound oxide high-T_C superconductor. The use of an inert-gas ion species in these devices is extremely important as Ga implantation into superconducting materials has previously been shown to suppress superconductivity. The extremely small probe size of the He GFIS has allowed us to create sub-20nm apertures in a variety of materials. Sub-20nm apertures in InAs nanowires and in graphene have been fabricated for experiments in quantum coherent electronics and quantum nanophotonics respectively.

Authors Index

Bold page numbers indicate the presenter

— A —

Alkemade, P.F.A.: HI+2D+AS+MC-ThA8, 1

— B —

Bagnall, D.M.: HI+2D+AS+MC-ThA9, 2

Boden, S.A.: HI+2D+AS+MC-ThA9, **2**

Braz, N.: HI+2D+AS+MC-ThA10, 2

— C —

Cumpson, P.J.: HI+2D+AS+MC-ThA3, 1

— F —

Fliervoet, T.: HI+2D+AS+MC-ThA8, 1

— H —

Hoefnagels, R.: HI+2D+AS+MC-ThA8, 1

— J —

Jackman, R.B.: HI+2D+AS+MC-ThA10, 2

— K —

Kalhor, N.: HI+2D+AS+MC-ThA8, **1**

— L —

Livengood, R.H.: HI+2D+AS+MC-ThA4, 1;
HI+2D+AS+MC-ThA6, **1**

— M —

Maas, D.J.: HI+2D+AS+MC-ThA8, 1

Meessen, J.: HI+2D+AS+MC-ThA8, 1

Mulckhuysse, W.: HI+2D+AS+MC-ThA8, 1

— N —

Nash, C.: HI+2D+AS+MC-ThA10, 2

Nguyen, T.-T.: HI+2D+AS+MC-ThA10, 2

— O —

Ogawa, S.: HI+2D+AS+MC-ThA1, **1**

— P —

Portoles, J.F.: HI+2D+AS+MC-ThA3, **1**

— R —

Rack, P.D.: HI+2D+AS+MC-ThA4, 1

— S —

Sagar, J.: HI+2D+AS+MC-ThA10, **2**

Shi, X.: HI+2D+AS+MC-ThA9, 2

Sourribes, M.J.L.: HI+2D+AS+MC-ThA10, 2

— T —

Tan, S.: HI+2D+AS+MC-ThA4, 1;

HI+2D+AS+MC-ThA6, 1

Timilsina, R.: HI+2D+AS+MC-ThA4, **1**

— V —

van Langen-Suurling, A.: HI+2D+AS+MC-ThA8,
1

van Veldhoven, E.: HI+2D+AS+MC-ThA8, 1

Verspaget, C.: HI+2D+AS+MC-ThA8, 1

— W —

Warburton, P.A.: HI+2D+AS+MC-ThA10, 2

Wootton, T.: HI+2D+AS+MC-ThA10, 2

Wuister, S.: HI+2D+AS+MC-ThA8, 1