Advanced Ion Microscopy and Ion Beam Nano-engineering Focus Topic
Room 301 - Session HI-ThA

Novel Beam Induced Material Engineering and Nano Patterning

Moderators: Frances Allen, UC Berkeley, **Annalena Wolff**, Caltech

2:20pm **HI-ThA-1 Additive Nano-Manufacturing of Advanced Superconductors, and Devices Using Focused Ion Beam Technology*, Rosa Córdoba,*** Institute of Molecular Science (ICMol), University of Valencia, Spain **INVITED**

Superconducting materials are dissipationless carriers of electric current and provide macroscopic and robust quantum coherence. These properties render them highly valuable as parts for electrical generators, magnetic sensors, and powerful magnets. To achieve the required performance employed in those applications, bulk superconductors often need nanoengineering. Moreover, when these materials are reduced to the nanoscale becoming **nanosuperconductors**, exciting new physical phenomena emerge. This has encouraged the study of their performance as 1D quantum oscillators and Josephson junction arrays as essential elements to be implemented in circuits.

Ground-breaking proposals have taken advantage of the third dimension (3D) for the development of advanced electronic components, opening fascinating novel routes in the fields of material science, physics and nanotechnology. Thus, **3D nanosuperconductors** could be implemented in future highly-efficient electronic elements. However, their fabrication and characterization remain a challenge.

In this contribution, we introduce a direct-write additive nano-manufacturing method based on focused ion beam technologies to fabricate advanced nano-superconductors at-will. This technique called focused ion beam induced deposition (FIBID) is based on CVD process assisted by an ion beam focused to a few nanometers.

We have prepared 3D superconducting hollow nanocylinders with controllable inner and outer diameters (down to 32 nm), and nanohelices with at-will geometries, by decomposing a precursor with a He^+ FIB [1,2]. These nanostrucutres become superconducting at 7 K and show large critical magnetic field and critical current density.Remarkably, these nanohelices display superconductivity up to 15 T depending on the direction of the field with respect to the nanohelix axis. This suggest that their helical 3D geometry and their orientation in a magnetic field play a significant role in the superconducting phase transition. Moreover, fingerprints of vortex and phase-slip patterns are also experimentally identified and supported by numerical simulations based on the time-dependent Ginzburg-Landau equation[3].

Additionally, we present an experimental work on the modulation of electric field-induced superconductivity in 45 nm-wide nanowires fabricated using Ga^+ FIB[4]. A theoretical model based on the GL theory explains this modulation by the squeezing of the superconducting state by the electric field.

[1]R. Córdoba et al., *Nano Lett.***2018**, *18*, 1379.

[2]R. Córdoba et al., *Beilstein J. Nanotechnol.***2020**, *11*, 1198.

[3]R. Córdoba et al., *Nano Lett.***2019**, *19*, 8597.

[4]P. Orús et al., *Sci. Rep.***2021**, *11*, 17698.

3:00pm **HI-ThA-3 On Demand Spatially Controlled Fabrication of Single Photon Emitters in Si*, Gregor Hlawacek,*** *N. Klingner, M. Hollenbach, U. Kentsch, G. Astakhov,* Helmholtz-Zentrum Dresden - Rossendorf, Germany

Single photon emitters (SPE) are fundamental building blocks for future quantum technology applications. However, many approach lack the required spatial placement accuracy and Si technology compatibility required for many of the envisioned applications. Here, we present a method to fabricate at will placed single or few SPEs emitting in the telecom O-band in Silicon [1] . The successful integration of these telecom quantum emitters into photonic structures such as micro-resonators, nanopillars and photonic crystals with sub-micrometer precision paves the way toward a monolithic, all-silicon-based semiconductor-superconductor quantum circuit for which this work lays the foundations. To achieve our goal we employ home built AuSi liquid metal alloy ion sources (LMAIS) and an Orsay Physics CANION M31Z+ focused ion beam (FIB). Silicon-on-insulator substrates from different fabrication methods have been irradiated with a spot pattern. 6 to 500 Si^{2+} ions have been implanted per spot using an energy of 40 keV. For the analysis and confirmation of the fabrication of true SPEs a home build photo luminescence setup has been used. G-centers formed by the combination of two carbon atoms and a silicon atom are confirmed by measurements of zero phonon lines (ZPL) at the expected wave length of 1278 nm for the case of carbon rich SOI wafers. In the case of ultra clean SOI wafers and high ion fluxes emission from tri-interstitial Si complexes is observed. The SPE nature of these so called W-centers has also been confirmed by ZPL measurements at 1218 nm. The achieved lateral SPE placement accuracy is below 100 nm in both cases and the success rate of SPE formation is more than 50%. After a discussion of the formation statistic we also present an approach how our FIB based approach can be upscaled to wafer-scale nanofabrication of telecom SPEs compatible with complementary metal oxide semiconductor (CMOS) technology for very large scale integration (VLSI).

[1] M. Hollenbach, N. Klingner, N. S. Jagtap, L. Bischoff, C. Fowley, U. Kentsch, G. Hlawacek, A. Erbe, N. V. Abrosimov, M. Helm, Y. Berencén, and G. V. Astakhov, “Wafer-scale nanofab-rication of telecom single-photon emitters in silicon,” (2022), arXiv:2204.13173 [quant-ph].

3:20pm **HI-ThA-4 Towards FIB Patterning of Reconfigurable Plasmonic Arrays*, Ivan Kravchenko,*** *N. Lavrik,* Center for Nanophase Materials Sciences, Oak Ridge National Laboratory

Arrays of deterministic plasmonic nanoparticles have numerous applications in areas spanning from analytical chemistry, to catalysis, to biomedicine. E-beam lithographic patterning of metal films on inorganic substrates is a well-established technological strategy that enables implementation of 2D arrays of plasmonic particles of various shapes and arrangements with arbitrary complexity [1]. However, existing approaches to creating such arrays are limited to solid substrates that are insoluble in organic solvents since development of e-beam resists relies on the use of ketones or similar solvents that tend to attack or dissolve polymers. Here we explore a novel system in which advanced FIB milling is used to pattern arrays of plasmonic nanoparticles on a polymer film that can be liquified by increasing its temperature above its glass transition point and, therefore, provide a nanofluidic interface and, in turn, a pathway to changing the nanoparticle arrangement by external stimuli. Our initial proof of principle experiments focused on arrays of Au nanoparticles with broken symmetry (Figure 1, Supplemental Document) that can attain mobility due to photothermal or thermophoretic excitation [2].

A Raith Velion focused ion beam/scanning electron microscope (FIB/SEM) was used to mill 25 nm thick Au film sputtered on ZEP520A electron beam resist that coated a silicon substrate. ZEP520A e-beam resist was selected as a copolymer compatible with spin coating and commonly available in a cleanroom setting. Its glass transition point of about 180C makes it a good candidate for experiments in which it can be liquified under photothermal or thermal excitation.

To avoid contamination of the Au film, the FIB milling was done by a doubly ionized gold (Au^{++}) ions at an energy of 35 kV. The beam current of 22 pA provided a sub 20 nm resolution. The dose of ion beam exposure was varied from 500 to 5000 mC/cm^2. The arrays of patterned nanoparticles were characterized by SEM, optical microscopy and Raman spectroscopy. Evolution of the nanoparticle shapes and arrangements were monitored during the FIB milling and subsequent thermal activation experiments.

Acknowledgement

This work was supported by Center for Nanophase Materials Sciences (CNMS), which is a US Department of Energy, Office of Science User Facility at Oak Ridge National Laboratory

References

1. R. Dallapiccola, A. Gopinath, F. Stellacci, and L. Dal Negro, "Quasi-periodic distribution of plasmon modes in two-dimensional Fibonacci arrays of metal nanoparticles," Opt. Express 16, 5544-5555 (2008).

2. Liu, M., Zentgraf, T., Liu, Y. *et al.* "Light-driven nanoscale plasmonic motors". *Nature Nanotech* 5, 570–573 (2010).

3:40pm **HI-ThA-5 Low Energy Ion Beam Backside Circuit Edit Applications in FinFET Devices***, M. Raza, R. Livengood , T. Malik, O. Sidorov, Z. Malamud, I. Ronen,* ***Shida Tan,*** Intel Corporation*; M. Wong,* Thermofisher Scientific

Circuit Edit (CE) using Focused Ion Beams (FIB) has been widely adopted in the industry to validate known circuit and design marginality issues, test circuit design changes, and generate engineering samples [1]. An approach, commonly known as backside CE, is to access the transistor cell and lower level interconnects of interest through the bulk silicon. The highly localized FIB milling continues until Shallow Trench Isolation (STI) region or the transistor fins are exposed. This FIB exposed trench is commonly referred to as a Node Access Hole (NAH) and it is within this area that subsequent CE tasks such as, accessing, cutting, or rerouting of lower level signals take place [2]. At the most commonly used ion beam energy of 30 KeV, Ga^+ Ion beam penetration depth, can negatively affect circuit performance by altering the intrinsic device parameters. In order to preserve the functionality of the neighboring active devices, machining geometries need to be limited by the transistor cell size and ion beam material interaction volume

An obvious approach in reducing ion material interaction volume is to operate at lower ion beam energy [3].At reduced beam energy, the lateral machining geometry can increase in size due to reduction in the ion material interaction range.In a FinFET device, the transistor channel is located at the tip of the fin, 50 to 70 nm from the bulk substrate - STI interface. Sufficient reduction in the ion beam material interaction volume also allows non-invasive machining directly over-active transistors.

In this work, we present a new approach in using low energy Ga^+ Ion beams at 5 KeV energy for NAH preparation. At low ion beam energy, we demonstrated that the NAH dimension is no longer limited by the cell size.We will present simulation data on interaction volume of the ion beams relative to the depth of the channel in FinFET, showcasing the effectiveness of low energy Ga^+ beams. Finally, we will present empirical results measuring timing impact of ion beam machining on free running ring oscillator test structures and will show example edit results on latest generation process node devices.

Author Index

Bold page numbers indicate presenter