Nanoscale Science and Technology
Room 206 A W - Session NS1-MoM

Frontier in Nanoscale Electron, Ion, and Scanning Probe Imaging

Moderators: Marek Kolmer, Ames National Laboratory, **Robertus Elberse**, NIST

8:15am **NS1-MoM-1 Design, Construction, and Performance of a Dilution Refrigerator-Based Esrspm System with Cryogenic Switches**, ***Robertus Elbertse***, *Dengyu Yang, Sungmin Kim, Dilek Yildiz, Daniel Walkup, Steven Blankenship, Joseph Stroscio,* NIST **INVITED**

Electron Spin Resonance using a Scanning Tunneling Microscope (ESRSTM) relies on reaching crogenic temperatures to achieve favorable thermal population distributions of quantum states. To date, most ESRSTMs operate between 300 mK and 4 K. Here, we present an ESRSTM that can operate down to 10 mK using a dilution refrigerator (DR). The design of the system is multi-modal, combining STM, AFM, electrical transport and ESR measurement capabilities. To characterize the microwave transmission, we have measured the frequency-dependent radio frequency (RF) transmission using a Josephson tunnel junction, consisting of an Al probe tip and Al (111) sample at 10 mK. Excellent transmission was observed up to 40 GHz in comparison to previous measurements in other laboratories. At the base temperature of the DR (10 mK) scanning tunneling spectroscopy can reach an energy resolution of ≈10 μeV, comparable to the energy broadening expected at base temperature [1]. However, when RF lines are sufficiently transmissive, as we have measured in our DR ESRSPM, the thermal noise introduced by photons originating at room temperature can cause increased broadening effects. This may reach orders of magnitude higher than broadening given by the base temperature of the DR. We will show how adding attenuators and cryogenic switches may help reduce such photonic noise and subsequently show its effect on the decoherence time of single atom qubits.

[1] J. Schwenk *et al.*, "Achieving μeV tunneling resolution in an in-operando scanning tunneling microscopy, atomic force microscopy, and magnetotransport system for quantum materials research," *Rev. Sci. Instrum.*, vol. 91, no. 7, p. 071101, Jul. 2020, doi: 10.1063/5.0005320.

8:45am **NS1-MoM-3 Magnetic Coupling in Graphene Nanoribbon Quantum Dots and Looking Beyond**, ***Percy Zahl***, Brookhaven National Laboratory*; Alexander Sinitskii, Mamun Sarker,* University of Nebraska-Lincoln, USA*; Peter H. Jacobse, Michael F. Crommie,* University of California, Berkeley*; Anshul Saxena,* Walker Department of Mechanical Engineering University of Texas*; Ziyi Wang,* Materials Sciences Division Lawrence Berkeley National Laboratory Berkeley*; Emma Berger,* Department of Physics University of California, Berkeley*; Narayana R. Aluru,* Walker Department of Mechanical Engineering University of Texas

Carbon-based quantum dots (QDs) enable flexible manipulation of electronic behavior at the nanoscale, but controlling their magnetic properties requires atomically precise structural control. While magnetism is observed in organic molecules and graphene nanoribbons (GNRs), GNR precursors enabling bottom-up fabrication of QDs with various spin ground states have not yet been reported. Here the development of a new GNR precursor that results in magnetic QD structures embedded in semiconducting GNRs is reported.

Inserting one such molecule into the GNR backbone and graphitizing it results in a QD region hosting one unpaired electron. QDs composed of two precursor molecules exhibit nonmagnetic, anti ferromagnetic, or anti ferromagnetic ground states, depending on the structural details that determine the coupling behavior of the spins originating from each molecule.

We present on surface precisely synthesized GNR structures imaged using high-resolution atomic force microscopy (HR-AFM) together with high resolution scanning tunneling spectroscopy (STS) to identify local spin properties localized at specific sites within those carbon based structures at the atomic scale.

The synthesis of these QDs and the emergence of localized states are demonstrated through HR-AFM, scanning tunneling microscopy (STM) imaging, and spectroscopy, and the relationship between QD atomic structure and magnetic properties is uncovered. GNR QDs provide a useful platform for controlling the spin-degree of freedom in carbon-based nano structures.

Looking Beyond: Such structures are promising molecular building blocks of carbon based future devices with spin controllable or quantum computing capable elements. Challenges remain to build or move such structures from metal support onto insulating surfaces to decouple spins from the substrate and create a potentially significant long de-coherence time to be practically useful. Furthermore control and readout certainly will be challenging. First steps have been demonstrated using SPM techniques and manipulation on atomic scale. Still, instrumentation has to allow for convenient and efficient future experiments.

Reference to this work:

[1] Small 2024, 20, 2400473; DOI: 10.1002/smll.202400473

9:00am **NS1-MoM-4 Direct Observation of Mg Diffusion Through Screw-type Dislocations in a GaN Device Using Atom Probe Tomography**, ***Yimeng Chen***, *Michael Salmon, Xiuhong Han,* EAG Laboratories

Large band gap vertical GaN power devices have been developed for high efficiency switch devices [1]. These devices incorporate p-type GaN through Mg doping in selective regions. Precise control of dopant concentration is crucial for semiconductor devices. However, interfacial diffusion or through defect migration of dopants can degrade the performance. Dopant segregation at threading dislocations inducing current leakage was reported [2].

We analyzed a GaN device removed from a USB charger, purchased from the market, that contained the NV6125 microchip for power switching control. The microchip was mechanically de-processed at EAG down to the field-effect-transistor level, exposing the source/drain region for microstructural characterization. A ~0.5 μm thick lamella in cross-section was made along the gate via Focused Ion Beam (FIB) and observed using Scanning Transmission Electron Microscopy (STEM). STEM observation confirmed a layered structure composed of dielectric oxide, metal contact, p-type GaN and AlGaN layers on GaN. The GaN epi exhibits a high threading dislocation density (TDD) that we estimate to be ~1E9/cm^2. Using a simple 2-beam tilting strategy in STEM, we were able to identify each dislocation as either edge, screw, or mixed type.

Precise STEM carbon-deposition was utilized to mark and target defect free regions as well as individual dislocations. Small pillars, ~0.5μmx0.5μmx4μm, containing the marked locations from the existing STEM lamella were extracted and welded to specific grids suitable for both APT and STEM. The samples were then re-imaged and marked again in STEM. Using the STEM marks to guide further FIB machining, the pillars were further processed into needle-shaped samples suitable for atom probe tomography (APT), centered at the precise locations of the threading defects. Composition and elemental distribution, in and around dislocations, were studied using APT. In the presentation, we will compare dopant distribution in dislocation-free regions and at dislocation cores.

APT analysis confirmed approximately 100 ppm Mg dopant in the p-type GaN region. The results clearly indicate Mg diffusion along the dislocation core through the electron blocking layer, resulting in a line concentration of ~80 dopant atom per 100 nm inside the GaN. The study demonstrates the unique capability of site-specific analysis of defects in device structures using correlative STEM and APT analysis, providing detailed insight into the diffusion behavior of dopant in and around threading defects.

[1] T. Oka, T. Ina, Y. Ueno, J. Nishii, Appl. Phys. Express 2015, 8, 6.

[2] H. Sakurai, et. al., Appl. Phys. Express 2020, 13, 086501.

9:15am **NS1-MoM-5 Focused Ion Beam Low Energy Implantation**, ***Alex Belianinov***, *Michael Titze, Chris Smyth,* Sandia National Laboratories*; Jonathan Poplawsky,* Oak Ridge National Laboratory*; Barney Doyle,* Sandia National Laboratories

Ion implantation is a key capability for the semiconductor industry. As devices shrink, novel materials enter the manufacturing line, and quantum technologies transition to being more mainstream, traditional implantation methods fall short in terms of energy, ion species, and positional precision. However, lowering the implantation energy while maintaining nanometer scale spot size is a technological challenge. This presentation will show an overview of techniques at Sandia National Laboratories Ion Beam Facility that allow focused ion implants 10-200 keV range for quantum relevant applications.

Additionally new developments in sub-1 keV focused ion implants into Si and 2D devices, using a focused ion beam system, validated by atom probe tomography will be shown. We illustrate that identical results for low energy ion implants can be achieved by either lowering the column voltage, or decelerating ions using bias – while maintaining good spatial resolution.

Furthermore, our data reveal that standard implant modeling approaches overestimates experimental depth by a significant margin. Finally, we discuss how our results pave a way to much lower implantation energies, while maintaining high spatial resolution.

9:30am **NS1-MoM-6 Silicon-Containing Poly(Phthalaldehyde) Hard Mask Materials for Simplified High-Resolution and Grayscale Patterning via Thermal Scanning Probe Lithography (t-SPL) - A NanoFrazor Use Case**, ***Nicholas Hendricks***, *Emine Çağin,* Heidelberg Instruments Nano AG, Switzerland

Enabled by the NanoFrazor technology, thermal scanning probe lithography (t-SPL) has established itself as a mature and reliable direct-write nanolithography technique for generating nanoscale structures [1-4]. The NanoFrazor technology offers an alternative and complementary process to conventional lithography techniques of photolithography and electron-beam lithography (EBL). With an advanced cantilever, t-SPL generates patterns by scanning an ultrasharp tip over a sample surface to induce local changes with a thermal stimulus, which allows for various modifications to the sample via removal, conversion, or addition. Along with an ultrasharp tip, the t-SPL cantilever contains other important functions such as an integrated thermal height sensor and an integrated heating element, both of which are advantageous for fabricating devices for quantum computing, nanoelectronics, and photonics.

The main thermal imaging resists used in t-SPL are poly(phthalaldehyde) (PPA) based materials that are commercially available from Allresist and Polymer Solutions. PPA is an all-organic based resist capable of direct sublimation when exposed to temperatures greater than the decomposition temperature, ~180°C. With such characteristics, PPA has been able to produce sub-10nm lateral dimensions while providing sub-nm vertical resolution but with limited etch selectivity in oxygen-based reactive ion etches. To overcome this, t-SPL utilizes a four-layer film stack, that includes a silicon-containing hard mask, deposited either by spin-coating or evaporation, for high-resolution patterning. To simplify the high-resolution patterning process, a two-layer film stack utilizing a spin-coatable silicon-containing PPA (Si-PPA) material, functioning both as a hard mask material and a thermal imaging resist, is assessed here. One of the advantages of using Si-PPA is that a simplified film stack is used (from four steps to two steps) while maintaining sub-20nm processing capabilities.

Within this presentation, the background of t-SPL will be introduced as well as the experimental results of the two-layer film stack for high-resolution patterning. Sub-40nm patterns transferred into a silicon substrate and sub-20nm features patterned into the Si-PPA film by t-SPL will be further elaborated upon. Initial results from grayscale patterning generated in Si-PPA films and etch amplifications will be discussed.

[1] S. Howell et al., Microsystems & Nanoengineering, 6, 21 (2020)

[2] V. Levati et al., Adv. Mater. Technol. 8, 2300166 (2023)

[3] L. Shani et al., Nanotechnology, 35, 255302 (2024)

[4] Mukherjee et al., ACS Nano, 19, 9327 (2025)

9:45am **NS1-MoM-7 Tunable Electronic Properties Within Highly Unoccupied Electronic Bands of Graphene-SiC Heterostructures Determined by Scanning Tunneling Spectroscopy**, ***Marek Kolmer***, *Umamahesh Thupakula, Shen Chen,* Ames National Laboratory*; Hoyeon Jeon,* Oak Ridge National Laboratory*; Wonhee Ko,* The University of Tennessee, Knoxville*; An-Ping Li,* Oak Ridge National Laboratory*; Michael C. Tringides,* Iowa State University

Manipulation of the interlayer couplings in vertically stacked two-dimensional (2d) materials results in highly tunable electronic properties, often stemming from emerging novel electronic and topological phases. Here, we will focus on the epitaxially grown graphene (EG) on a silicon carbide (0001) surface, where thermal decomposition of the top silicon carbide layers provides a synthesis of epitaxial graphene layer(s) with exceptional uniformity and control over their structural properties, i.e., number of graphene layers. Subsequent intercalation of heteroatoms under graphene layer(s) becomes a promising strategy for the synthesis of designer 2d quantum materials. In the talk we will discuss how control over these buried graphene interfaces and metal intercalation affects the resulting electronic structure of these model systems. In particular, we will focus on the less understood interface states located within the unoccupied electronic band regime above the vacuum level. Such states, especially for energies larger than ~20 eV, are not easily accessible with most spectroscopies, while here, both the pristine and intercalated systems can be easily measured and compared. The low-temperature scanning tunneling microscope operating in the high-sample bias voltages reaching ~40 V is used to study the interaction between the interface states and high-bias resonances formed within the triangular tip-sample potential. We show the methodology of how to extract the intrinsic electronic density of states of highly unoccupied bands as a function of graphene thickness and intercalated phase from these high-bias scanning tunneling spectroscopy (STS) experiments. Due to the 2d nature of systematically studied graphene heterostructures, their high-bias STS spectra show pronounced features within this energy regime, i.e., in contrast to typical bulk, half-plane metals' spectra, which strongly depend on the interlayer couplings between the heterostructure interfaces.

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