

Spatiotemporal Imaging of Magnetization Dynamics of Van der Waals Ferromagnet Fe_5GeTe_2

CNF Project Number: 2091-11

Principal Investigator(s): Gregory D. Fuchs

User(s): Julie Soho Shim

Affiliation(s): Department of Physics, Cornell University, School of Applied and Engineering Physics, Cornell University

Primary Source(s) of Research Funding: Department of Energy Office of Science, Basic Energy Sciences (DE-SC0019997)

Contact: gdf9@cornell.edu, jss545@cornell.edu

Primary CNF Tools Used: AJA Orion Sputtering Systems, Heidelberg MLA 150 Maskless Aligner, Oxford 81/82, DISCO Dicing Saw, Westbond 7400A Ultrasonic Wire Bonder

Abstract:

Two-dimensional (2D) magnetic materials offer a rich landscape for exploring spin dynamics and topological textures, with tunable properties and compatibility with heterostructure engineering. Among these, a 2D ferromagnet Fe_5GeTe_2 (F5GT) has emerged as a promising candidate due to its high Curie temperature (T_c). However, the magnetism of F5GT is highly sensitive to thermal history and sample inhomogeneity, making per-flake characterization necessary. Here, we present a scanning diamond nitrogen-vacancy (NV) magnetometry study where the flakes are transferred onto a patterned loop antenna. We observe near- T_c magnetic domain formation and stabilization for both furnace-cooled and quench-cooled flakes. Furthermore, we observe distinct magnetic domain features between the two samples: the quench-cooled flake develops fine-scale magnetic domains elongated predominantly in a single direction, whereas the furnace-cooled flake exhibits multiple nematic domain directions. This work can offer new insights into the nanoscale magnetism and local magnetic configurations of van der Waals ferromagnets.

Summary of Research:

Two-dimensional (2D) magnets have garnered significant attention for hosting exotic magnetic phenomena and topological spin textures, arising from strongly enhanced intrinsic spin fluctuations [1]. Their magnetic properties are readily tunable through external fields, strain, or

chemical modifications, and their cleavable nature enables seamless integration into engineered heterostructures [1]. These features position 2D magnets as versatile platforms for probing fundamental spin interactions and developing multifunctional devices that integrate electronic, optical, and magnetic properties. Despite their intriguing properties, many two-dimensional ferromagnetic materials exhibit Curie temperatures (T_c) significantly below room temperature, restricting their practical use. F5GT has been identified as a promising candidate demonstrating a T_c of up to 332 K in bulk and 280 K in exfoliated thin flakes (~ 10 nm) [2]. Additionally, a recent photoemission electron microscopy (PEEM) study reported possible sample inhomogeneity in F5GT crystals, revealing a coexistence of out-of-plane and in-plane magnetic domains likely tied to chemical inhomogeneities such as Fe vacancies [3]. Understanding the single flake magnetic properties will be key to future applications.

To better assess per-flake magnetic properties, we perform scanning NV measurements using exfoliated F5GT flakes from two crystals: a quench-cooled F5GT crystal and a furnace-cooled F5GT crystal. For this purpose, we design and fabricate loop antennas and transfer exfoliated F5GT flakes onto them, enabling imaging of their nanoscale magnetic domains.

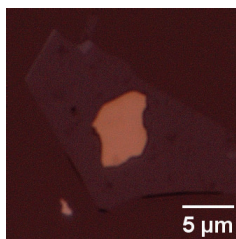


Figure 1: F5GT flake transferred onto the patterned loop antenna. A larger, close-to-transparent flake is the hBN flake capping the F5GT flake.

Fabrication:

Loop antennas were fabricated by patterning loop antenna onto a 2-inch sapphire (single-side-polished) wafer with the Heidelberg MLA 150 Maskless Aligner, followed by cleaning with Oxford 81/82, and sputtering Ti (10 nm)/Pt (150 nm) films. The patterned wafers were subsequently diced using a DISCO Dicing Saw. A nanoflake of F5GT, capped with hexagonal boron nitride (hBN), was transferred onto the center of the loop antenna (Fig. 1). For scanning NV measurements, the Westbond 7400A Ultrasonic Wire Bonder was used to wirebond the antenna to a rf circuit component.

Conclusions and Future Steps:

Using our variable-temperature scanning NV setup, we were able to capture the near- T_c ferromagnetic domain stabilization of the exfoliated flakes. Figure 2 shows the representative scanning NV images for variable temperatures, for a representative flake (28 nm thick furnace-cooled flake), taken with a probe-to-sample distance of 100 nm. As the temperature decreases, magnetic contrast becomes more pronounced and domain features nucleate, reaching a stray field contrast of approximately 10 G at 280 K, indicating the stabilization of ferromagnetic order.

Furthermore, we observe that the furnace-cooled flake and quench-cooled flake show different magnetic domain features at 280 K. Figure 3 shows scanning NV images of the furnace-cooled flake, measured at a probe-to-sample distance of 100 nm, and the quench-cooled flake, measured at a probe-to-sample distance of 200 nm. At this temperature, the 90 nm thick quench-cooled flake exhibits magnetic domain features that are elongated in an almost single direction (along the y-direction).

In contrast, the 28 nm thick furnace-cooled flake displays multiple nematic domain directions.

To further investigate the magnetic properties of F5GT flakes, we are planning to measure scanning NV images with varying bias magnetic field, which can allow us to further resolve the evolution of magnetic domain features and the underlying magnetic anisotropy.

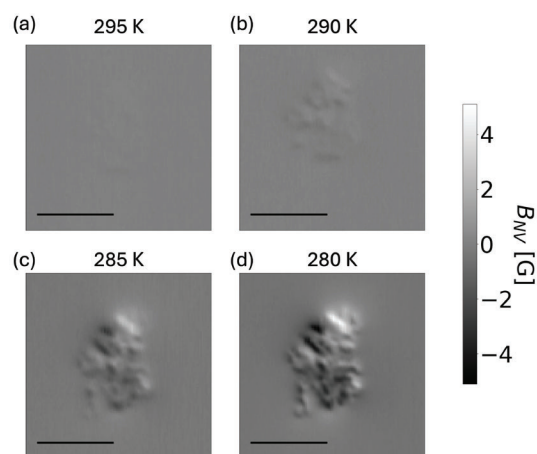


Figure 2: Stray magnetic field imaging of 28 nm thick, furnace-cooled F5GT flake at (a) 295 K, (b) 290 K, (c) 285 K, and (d) 280 K. The images were taken with a probe-to-sample distance of 100 nm. The scale bar represents 5 μ m.

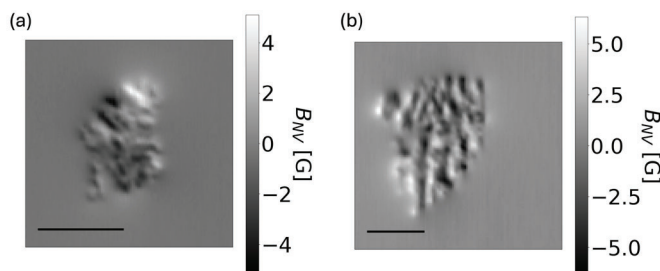


Figure 3: Stray magnetic field imaging of F5GT flakes at 280 K: (a) 28 nm thick, furnace-cooled F5GT flake, and (b) 90 nm thick, quench-cooled F5GT flake. The images were taken with a probe-to-sample distance of 100 nm for the furnace-cooled flake and 200 nm for the quench-cooled flake.

References:

- [1] K. S. Burch, D. Mandrus, and J.-G. Park, *Nature*, 563, 47-52 (2018).
- [2] A. F. May et al., *ACS Nano*, 13, 4436 (2019).
- [3] M. Ghidini et al., *ACS Nano* 19, 26193 (2025).

Spatiotemporal Imaging of Magnetization Dynamics at the Nanoscale

CNF Project Number: 2091-11

Principal Investigator(s): Gregory D. Fuchs

User(s): Yinshi Chen, Anabelle Brueggemann

Affiliation(s): Department of Applied and Engineering Physics, Cornell University[Text Wrapping Break]Department of Physics, Lafayette college

Primary Source(s) of Research Funding: The Center for Energy Efficient Magnonics Energy (CEEMag) Frontier Research Center (EFRC) funding, under national science foundation

Contact: gdf9@cornell.edu, yc2793@cornell.edu, alb477@cornell.edu

Research Group Website: <https://fuchs.research.engineering.cornell.edu/>

Primary CNF Tools Used: AJA Ion Mill, AJA Sputter 3, DISCO Dicing Saw, Filmetrics R50, Glen 1000 Resist Strip, Heidelberg MLA 150 Maskless Aligner, KLA P7 Profilometer, Westbond 7400A Ultrasonic Wire Bonder

Abstract:

We fabricated an RF antenna on sapphire substrate and microwave coplanar waveguide on LAFO chip for probing the magnon propagation in LAFO using our scanning NV setup. The fabrication process is done and mainly based on lift-off photolithography technique and thin film deposition.

Summary of Research:

Magnonic devices are promising candidates for next generation information processing technology for their low loss through transmission and tunable properties through electric and magnetic field [1]. We aim to image magnon propagation directly between different materials and are starting with simple propagation process in single LAFO layer. The experiment setup can be found in Figure 1, where the magnon is launched and received through a coplanar waveguide (CPW) and propagates in-plane on LAFO; the antenna below provides an interference field with the magnon stray field and make the optically detected magnetic resonance imaging possible through scanning NV; and NV center does the stray field readout from the green laser; also a global field is applied for bias on the NV ESR frequency. In this way, we can launch the magnon in a desired frequency range, and do the ODMR imaging and interference through global antenna at the same frequency [2]. The exact NV scanning measurement setup can be found in Figure 2, in which we use a rotating electromagnet for global bias field and a piezo-stage for LAFO sample moving and imaging. For the fabrication process of

the CPW and antenna as in Figure 3, we first clean the LAFO pieces and do lithography on the chips, then do the ion milling for defining the propagation area on LAFO, and do another lithography and sputtering for the coplanar waveguide fabrication. For the antenna, we just do a one step lift off and the sputter and we can fabricate them on the sapphire substrate (and finally dicing). The actual fabrication result can be found in Figure 4.

Conclusions and Future Steps:

We fabricated antennas and CPW for magnon propagation imaging based on the scanning NV setup. We will perform the scanning measurement and do propagation between layer experiment in future.

References:

- [1] P. Pirro, V. I. Vasyuchka, A. A. Serga, et al., "Advances in coherent magnonics," *Nature Reviews Materials* 6, 1114–1135 (2021). DOI:10.1038/s41578-021-00332-w
- [2] T. X. Zhou, J. J. Carmiggelt, L. M. Gächter, et al., "A magnon scattering platform," *Proceedings of the National Academy of Sciences* 118, e2019473118 (2021).

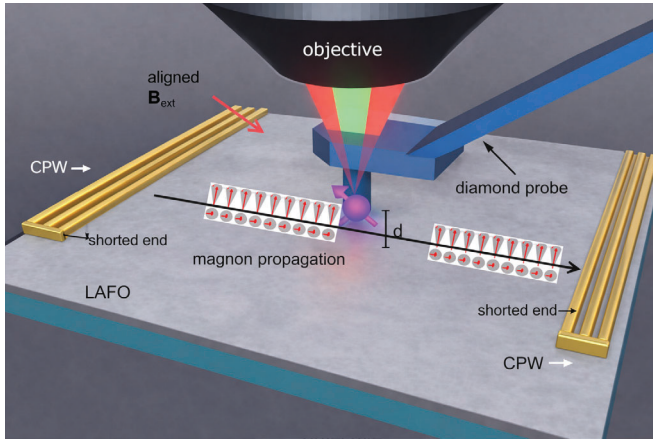


Figure 1: General setup for magnon propagation imaging using scanning NV.

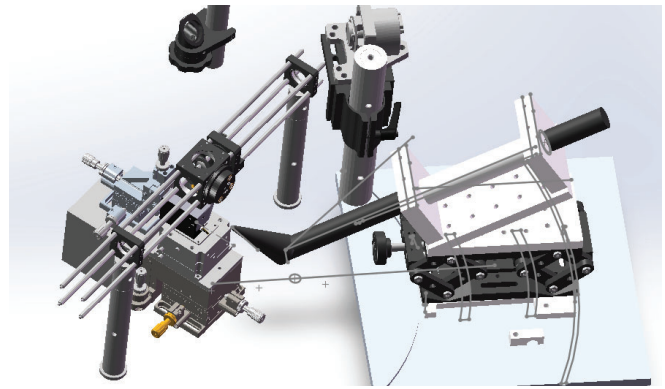


Figure 2: NV scanning setup.

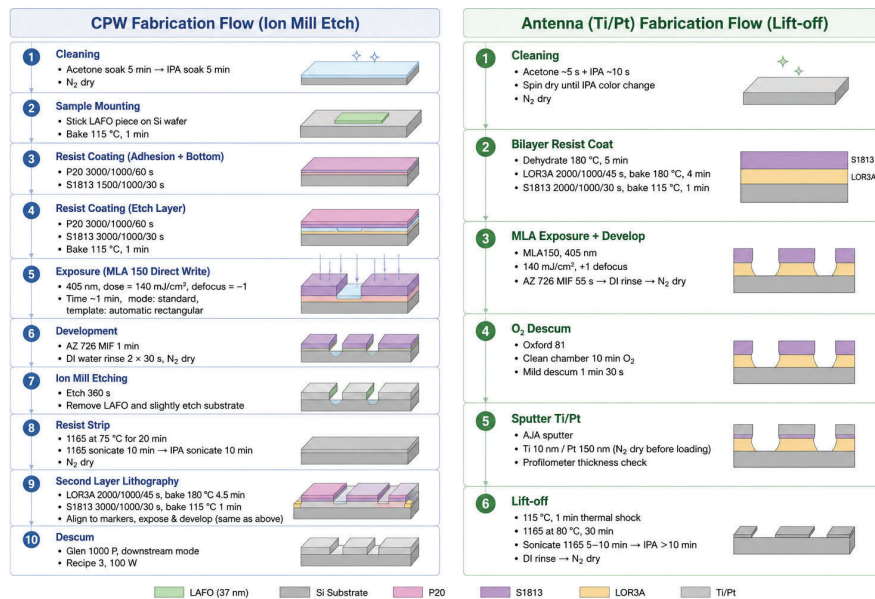


Figure 3: Fabrication process flow.

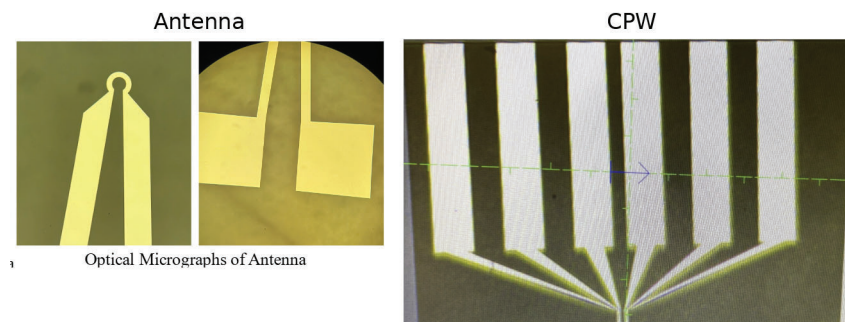


Figure 4: Device result.

Custom-Made Single-Crystal Silicon Cantilevers for Magnetic Resonance Force Microscopy

CNF Project Number: 2125-12

Principal Investigator(s): John A. Marohn

User(s): George R. Du Laney

Affiliation(s): Chemistry and Chemical Biology, Cornell University

Primary Source(s) of Research Funding: Cornell University

Contact: jam99@cornell.edu, grd44@cornell.edu

Website: <https://marohn.chem.cornell.edu/>

Primary CNF Tools Used: JEOL JBX9300FS

Abstract:

We employed e-beam lithography to prepare custom single-crystal silicon attonewton-sensitive microcantilevers for use in magnetic resonance force microscopy measurements. By using a focused-ion beam system to modify the bare cantilevers in a post-fabrication procedure, we can prepare magnet-tipped cantilevers with a variety of magnet shapes, sizes, and materials.

Summary of Research:

Magnetic resonance force microscopy (MRFM) is a scanning-probe technique used to resolve the locations of nuclear and electronic spins using principles of magnetic resonance. To accomplish this, we bring an attonewton-sensitive magnet-tipped microcantilever in proximity to a spin-polarized sample. The sample's polarization is modulated and the resulting changes to the cantilever's vibrational amplitude and frequency are recorded as the signal. A puzzle in recent electron spin resonance (ESR)-MRFM experiments is a factor of 17 in missing signal. This missing signal used to be greater, a factor of 340, and was ameliorated by modified sample preparation procedures [1].

To recover the remaining factor of 17 in signal, we are investigating potential sources of spin-lattice relaxation time (T₁)-shortening in our experiment. This is the focus of our investigation because a sample spin with a T₁ shorter than the oscillation period of our cantilever would not contribute significantly to the observed shift in the cantilever's mechanical resonance frequency.

Two potential sources of induced T₁-shortening are thermal magnetic fluctuations [2] and thermal current fluctuations [3]. Both of these causes can be investigated using blank fabricated cantilevers [4] and post-fabrication FIB-enabled modification [5].

We demonstrated that FIB can be used to attach magnetic particles ranging in size from ~400 nm to ~5 μm to blank cantilevers. The procedure can be used to mill particles to shapes of interest (i.e., cylinders), and to attach various magnetic materials. Significantly, this includes magnetic materials that are electrically insulating, like yttrium iron garnet (YIG). This last point is significant because it will allow us to address the theory that thermal current fluctuations are the cause of signal loss, whereby the degree of T₁ shortening is proportional to the magnet tip's conductivity.

Conclusions and Future Steps:

We have shown that the e-beam lithographically prepared silicon microcantilevers are suitable for post-fabrication modification in a FIB system. Future work may investigate the possibility of batch-fabricating magnet tips out of magnetic materials, such as YIG, so that the procedure can be applied to a more uniform starting point, rather than needing to mill a new shape from a microparticle every time.

References:

- [1] Boucher, M. C.; Isaac, C. E.; Sun, P.; Borbat, P. P.; Marohn, J. A., ACS Nano 2023, 17 (2), 1153–1165, DOI: 10.1021/acsnano.2c08635.
- [2] Stipe, B. C.; Mamin, H. J.; Yannoni, C. S.; Stowe, T. D.; Kenny, T. W.; Rugar, D., Phys. Rev. Lett. 2001, 87 (27), 277602, DOI: 10.1103/PhysRevLett.87.277602.
- [3] Kenny, J.; Mallubhotla, H.; Joynt, R., Phys. Rev. A 2021, 103 (6), 062401, DOI: 10.1103/PhysRevA.103.062401.
- [4] Hickman, S. A.; Moore, E. W.; Lee, S.; Longenecker, J. G.; Wright, S. J.; Harrell, L. E.; Marohn, J. A., ACS Nano 2010, 4 (12), 7141–7150, DOI: 10.1021/nn101577t.
- [5] Sun, P.; Du Laney, G. R.; Fuchs, T. M.; Oosterkamp, T. H.; Thomas, M. G.; Marohn, J. A., J. Vac. Sci. Technol. B 2026, 44 (4), 042803, DOI: 10.1116/6.0005501.

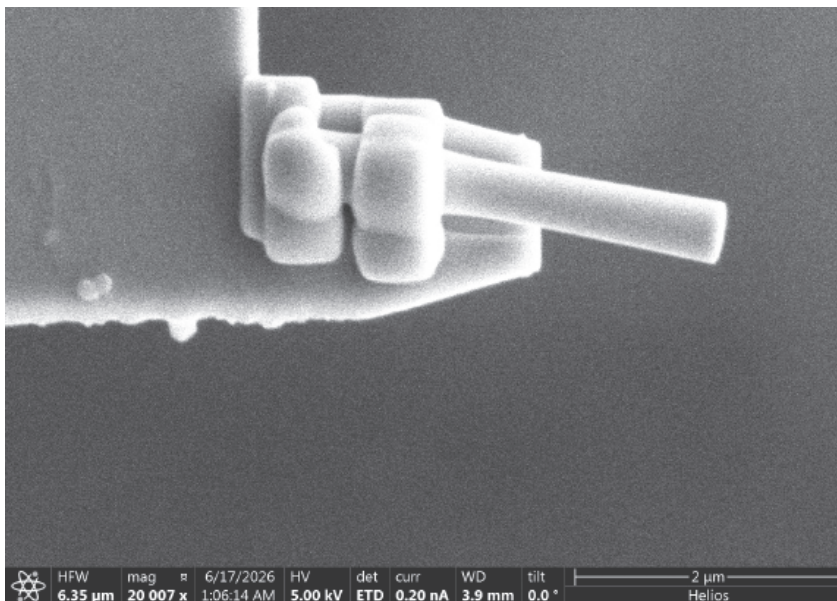


Figure 1: A 3.3 m-long, 480 nm-diameter cylinder of neodymium iron boron, ion-milled from a sphere and electrostatically transferred to the leading edge of a custom-made silicon cantilever. FIB-milled magnet tips affixed to lithographically prepared cantilevers will enable the exploration of different magnet materials and shapes in MRFM experiments.

Tunable Silicon Carbide Nanophotonics for Defect-Enhanced Optical Readout and Optically Detected Magnetic Resonance

CNF Project Number: 2126-12

Principal Investigator(s): Gregory Fuchs

User(s): Ying Yang

Affiliation(s): School of Applied and Engineering Physics, Cornell University

Primary Source(s) of Research Funding: National Science Foundation

Contact: gdf9@cornell.edu, yy2364@cornell.edu

Primary CNF Tools Used: JEOL 6300 EBL; Oxford 81 RIE; CVC SC4500 Evaporator; Zeiss Supra SEM, Zeiss Ultra SEM, LPCVD HTO & LTO

Abstract:

Silicon carbide-on-insulator (SiCOI) combines optically addressable spin defects with high-index-contrast photonics. We establish a fabrication process for microring-waveguide-grating devices, obtain room-temperature resonances with quality factor $Q \approx 6,500$, and extend the platform to implanted silicon-vacancy ensembles. At 77 K, V1, V1', and V2 emission was routed through the integrated photonics. By sweeping the radius and ring-waveguide gap, we tune cavity alignment and external coupling, producing strong, reproducible changes in the V1/V1' photoluminescence ratio and enhancement of V1. We also demonstrate the continuous-wave optically detected magnetic resonance (ODMR) of V2 ensembles at room temperature with magnetic-field and optical-power dependence. These results connect to cavity-assisted spin readout for chip-scale sensing.

Summary of Research:

Silicon carbide hosts color centers with optically addressable spins and near-infrared transitions, but bulk collection is limited by the material's high refractive index and weak zero-phonon-line emission [1–3]. SiCOI provides a route to increase useful photon collection by combining defect ensembles with optical resonators, waveguides, and grating couplers. Our work progress from fabrication development to defect-cavity coupling and spin-resonance measurements.

Our SiCOI devices are fabricated from a 540 nm 4H-SiC layer on 3.044 μm SiO_2 on Si substrate [4]. The PMMA495/PMMA950 bilayer resist is patterned by electron-beam lithography, followed by duty-cycled deposition and lift-off of a 100 nm Ni hard mask. The pattern is transferred to SiC by SF_6/O_2 reactive-ion etching, the Ni is removed, and approximately 2.5 μm SiO_2 is deposited as upper cladding (Fig. 1). Our etch

studies balanced sidewall taper against micromasking by tuning the SF_6/O_2 ratio, pressure and power. The optimized devices contain around 10 μm -radius rings, bus waveguides, and grating couplers with systematic radius, gap, and pitch variations.

The devices were characterized through two sets of fast-steering mirrors (FSM 4f-1 and FSM 4f-2) to control the excitation and collection paths (Fig. 2a). The confocal scan verifies the devices, and the strong PL at grating couplers suggests the efficient optical coupling into and out of the device. The non-confocal geometry excites one grating and collected from another to probe the T13 transmission of the waveguide-ring-waveguide structure. A representative optical ring TM₀₀ mode at 915.44 nm has 0.14 nm linewidth and $Q \approx 6,500$ (Fig. 2e).

To couple the ring modes with spin defects, we sweep the devices parameters. We change the ring radius R from 9.94 to 10.06 μm to shift the mode wavelength for spectral alignment with V1 near 861 nm and V2 near 916 nm; the ring-waveguide gap g from 0.14 to 0.10 μm to change the coupling condition of those ring modes and the bus waveguide from under-coupled and near-critical-coupled operation; and grating pitch from 0.39 to 0.62 μm to move the detection window and alter the relative TE and TM contributions.

For defect integration, the SiCOI chips are annealed, implanted with 50 keV He ions at $1 \times 10^{13} \text{ cm}^{-2}$, and post-annealed. At 77 K, V1', V1, and V2 emission are observed from the fabricated device [7]. Figure 3 gives V1 defect-cavity coupling. At fixed grating pitch, changing the ring radius shifts the ring resonance by about 1 nm for each 0.01 μm radius step. The V1/V1' peak ratio increases from 1.52 off resonance at $R = 9.99 \mu\text{m}$ to 14.6 on resonance at $R = 10.06 \mu\text{m}$. The normalized radius-wavelength map shows this systematic mode translation. At $R = 10.06 \mu\text{m}$, decreasing the ring-

waveguide gap g from 0.14 to 0.11 μm increases the V1/V1' ratio from 3.25 to 14.6 as the device moves toward critical coupling. Together, the radius and gap sweeps show that spectral alignment and waveguide–ring coupling independently control the routed V1 signal. These spectra demonstrate resonant spectral enhancement and integrated routing, complementing

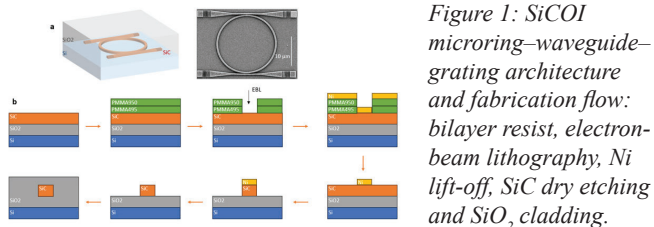
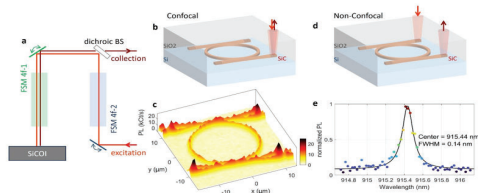


Figure 1: SiCOI microring-waveguide-grating architecture and fabrication flow: bilayer resist, electron-beam lithography, Ni lift-off, SiC dry etching and SiO₂ cladding.

Figure 2: Room-temperature optical characterization. (a) Optical setup. The light red excitation beam is controlled



by both fast-steering mirrors (FSM 4f-1 and FSM 4f-2) and the dark red collection beam is only controlled by FSM 4f-2. (b)-(c) The confocal scan map of the device shows that the ring and two coupling waveguides, equipped with four grating couplers, align precisely with the designed geometry. (d)-(e) The non-confocal emission from the SiCOI device shows the TM₀₀ ring resonance with a narrow linewidth and high Q -factor of 6500.

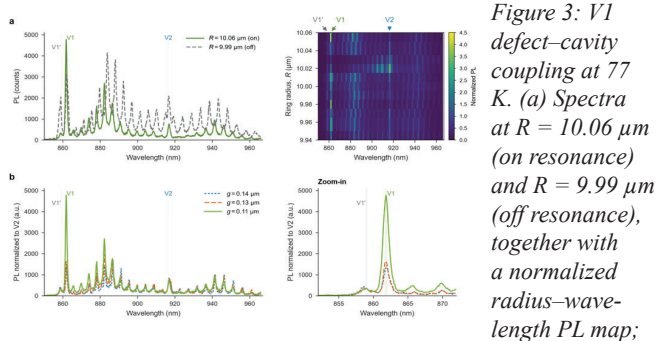
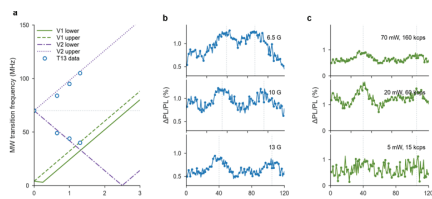


Figure 3: V1 defect-cavity coupling at 77 K. (a) Spectra at $R = 10.06 \mu\text{m}$ (on resonance) and $R = 9.99 \mu\text{m}$ (off resonance), together with a normalized radius-wave-length PL map;

the reported V1/V1' ratio changes from 1.52 off resonance to 14.6 on resonance. (b) Gap-dependent spectra at $R = 10.06 \mu\text{m}$ for ring-waveguide gaps of 0.11, 0.13, and 0.14 μm , shown over the full collection band and the V1 region. Increasing the gap moves the ring toward under-coupling and reduces the reported V1/V1' ratio from 14.6 to 3.25.

Figure 4: Continuous-wave ODMR of the V2 ensemble measured through T13 at room temperature. (a) Calculated V1 and V2 transition branches versus DC magnetic field HDC, with measured V2 resonances through T13. (b) Measured $\Delta\text{PL}/\text{PL}$ spectra at HDC = 6.5, 10, and 13 Gs; dashed guides mark the V2 branches. (c) $\Delta\text{PL}/\text{PL}$ spectra at HDC = 13 Gs for 70, 20, and 5 mW optical power, corresponding to 160, 60, and 15 kcps.



prior cavity-enhanced SiC color-center studies (5, 6). A lifetime measurement is still required to separate Purcell enhancement from changes in excitation and collection efficiency.

We next measure continuous-wave ODMR of V2 at room temperature in Figure 4, following established room-temperature V2 spin control.[8] The zero-field splitting at 70 MHz splits into two field-dependent branches with the DC magnetic field HDC; measured resonances from HDC = 6.5–13 Gs follow the expected V2 transition trend (Fig. 4b). Optical-power sweeps from 5 to 70 mW increase the detected rate from approximately 15 to 160 kcps and made the resonance structure progressively clearer (Fig. 4c). These data establish spin addressability although background from V1 and cavity/waveguide modes and a technical-noise floor currently limit contrast for magnetic-field sensitivity application.

Conclusions and Future Steps:

We develop a tunable SiCOI photonic platform, coupled implanted V1 ensembles to the optical resonances, and observed V2 ODMR. The combined results move from optimizing fabrication process, to control optical modes, route defect emission, and support spin readout. Next steps are spatially PMMA-masked He implantation, lower-damage etching and annealing, resonant V1 excitation at 4 K, lifetime measurements, and pulsed ODMR to determine T_2^* and T_2 .

References:

- [1] Babin, C. et al. Fabrication and nanophotonic waveguide integration of silicon carbide colour centres with preserved spin-optical coherence. *Nature Materials* 21, 67–73 (2022). doi: 10.1038/s41563-021-01148-3.
- [2] Lukin, D. M. et al. 4H-silicon-carbide-on-insulator for integrated quantum and nonlinear photonics. *Nature Photonics* 14, 330–334 (2020). doi: 10.1038/s41566-019-0556-6.
- [3] Castelletto, S. et al. Silicon Carbide Photonics Bridging Quantum Technology. *ACS Photonics* 9, 1434–1457 (2022). doi: 10.1021/acsp Photonics.1c01775.
- [4] Yi, A. et al. Wafer-scale 4H-silicon carbide-on-insulator (4H-SiCOI) platform for nonlinear integrated optical devices. *Optical Materials* 107, 109990 (2020). doi: 10.1016/j.optmat.2020.109990.
- [5] So, J.-P. et al. Purcell Enhancement and Spin Spectroscopy of Silicon Vacancy Centers in Silicon Carbide Using an Ultrasmall Mode-Volume Plasmonic Cavity. *Nano Letters* 24, 11669–11675 (2024). doi: 10.1021/acs.nanolett.4c03233.
- [6] Crook, A. L. et al. Purcell Enhancement of a Single Silicon Carbide Color Center with Coherent Spin Control. *Nano Letters* 20, 3427–3434 (2020). doi: 10.1021/acs.nanolett.0c00339.
- [7] Nagy, R. et al. High-fidelity spin and optical control of single silicon-vacancy centres in silicon carbide. *Nature Communications* 10, 1954 (2019). doi: 10.1038/s41467-019-09873-9.
- [8] Widmann, M. et al. Coherent control of single spins in silicon carbide at room temperature. *Nature Materials* 14, 164–168 (2015). doi: 10.1038/nmat4145.

Trion Hall Effect in Electron-hole Double Layers

CNF Project Number: 2633-18

Principal Investigator(s): Jie Shan, Kin Fai Mak

User(s): Raghav Chaturvedi, Jinwoo Yu

Affiliation(s): Laboratory of Atomic and Solid State Physics, School of Applied and Engineering Physics; Cornell University

Primary Source(s) of Research Funding: DOE, NSF, AFOSR, Moore Foundation

Contact: jie.shan@cornell.edu, kinfai.mak@cornell.edu, rc669@cornell.edu, jy968@cornell.edu

Website: <https://sites.google.com/site/makshangroup/>

Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator System (NPGS), Angstrom E-Beam Evaporator, SC4500 Odd/Even-Hour Evaporator, Oxford 81/82 RIE, YES Asher, Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, Dicing Saw - DISCO

Abstract:

Exciton is a quasiparticle made of one electron and one hole bound by Coulomb attraction. Doping an exciton fluid with excess electrons or holes creates a fluid of trions that are bound states of two electrons and one hole or vice versa. Since trions carry a net charge, they can experience a Lorentz force under finite magnetic field and exhibit a Hall effect. In this work, we observe a trion Hall effect in Coulomb-coupled $\text{MoSe}_2/\text{WSe}_2$ double layers. Through magneto-transport measurements, we find that an electron-like Hall effect can emerge in the hole doped layer because of Coulomb drag of negatively charged trions. Our work opens pathways to realize trion-based quantum Hall phenomena.

Summary of Research:

Excitonic insulators (EIs) [1] form when the binding energy of electron-hole pairs exceeds the single particle bandgap in a semiconductor. EIs provide an ideal platform for studying bosonic quantum states of matter, such as exciton condensates [2]. Using van der Waals (vdW) semiconductors it's possible to study exciton transport by separating the electrons and holes to different layers of material. This approach has been used to flow an exciton current in Coulomb-coupled double layers [3] in the absence of magnetic field. Doping the exciton fluid with excess carriers creates a Bose-Fermi mixture. In the limit of strongly attraction between free carriers and excitons, an equilibrium fluid of

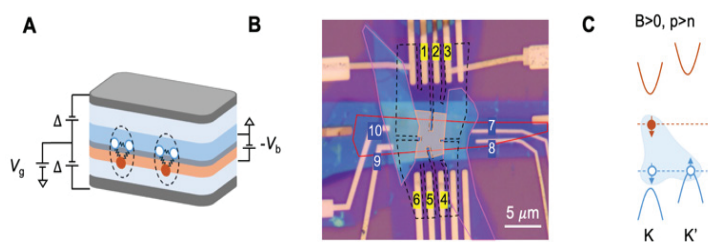


Figure 1: **A**, Schematic cross-section of the device. **B**, Optical microscope image of a device. Scale bar is 5 μm . **C**, Type-II band alignment of MoSe_2 and WSe_2 .

trions has been observed [4]. Since these trions are charged, they are subject to Lorentz forces under a perpendicular magnetic field [5].

Figure 1A and 1B show, respectively, a schematic cross-section and an optical image of our device. It consists of $\text{WSe}_2/\text{MoSe}_2$ double layers separated by a thin hexagonal boron nitride (hBN) barrier. WSe_2 and MoSe_2 form a type-II band alignment (Fig. 1C), that is, the lowest (highest) energy conduction (valence) band lies in the MoSe_2 (WSe_2) layer. The double layer is further encapsulated by two gates made of hBN and graphite. We use Pt and Bi electrodes that make Ohmic contacts to holes in the WSe_2 layer and electrons in the MoSe_2 layer, respectively. An interlayer bias, V_b , is applied between the layers to tune the electron-hole pair density, n_p , and the gate voltage V_g tunes electron-hole density imbalance. For negative V_g , excess holes are added to the WSe_2 layer and for positive V_g , excess electrons are added to the MoSe_2 layer.

Figure 2A and 2B show longitudinal (R_{xx}) and Hall (R_{xy}) resistances measured at $B = 4$ T in the

W-layer while the Mo-layer was in open-circuit. Since electrons are not allowed to flow, interlayer bound states in this measurement configuration are insulating states. The triangular insulating region near $V_g = 0$ is the EI. There are two additional insulating states that appear upon doping the EI with excess holes or electrons and are denoted by $(X+X^+)$ and $(X+X^-)$, respectively. These regions consist of bound excitons and trions – positive trions for $(X+X^+)$ and negative trions for $(X+X^-)$. Hall resistance is large inside the trion regions and changes sign for negative trions while measuring R_{xy} in the hole-doped layer. This effect can be explained by a Hall effect of trions since the hole in the hole layer experiences

trion region; n_H decreases monotonically due to free carriers forming bound trions. In the negative trion region, n_H becomes negative and jumps back to the hole density as the density increases and trions ionize. Figure 3B shows the temperature dependence of the Hall resistance in the positive and negative trion regions. Above 8 K, trions ionize into free carriers providing an estimate of the trion binding energy (~ 0.7 meV). The negative Hall resistance vanishes and the Hall resistance approaches the value corresponding to free hole density at high temperature.

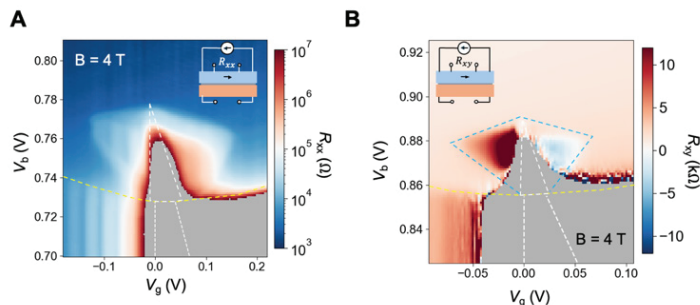


Figure 2: **A**, R_{xx} at $T = 1.5$ K as a function of V_g and V_b under $B = 4$ T, where R_{xx} is the longitudinal resistance measured on the hole layer with the electron layer in open circuit (inset). Blue dashed lines: boundary of the $(X+X^{\pm})$ regions. **B**, R_{xy} at $T = 1.5$ K as a function of V_g and V_b under $B = 4$ T.

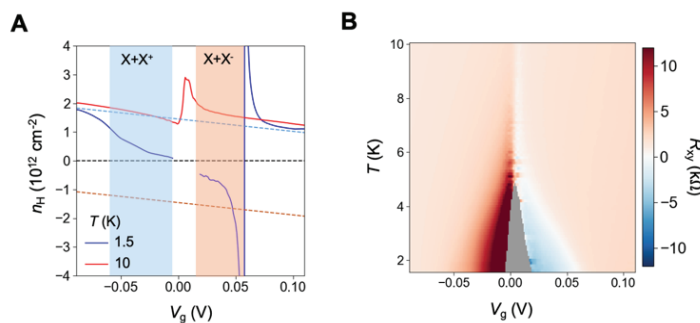


Figure 3: **A**, Hall density as a function of V_g at $V_b = 0.88$ V and $T = 1.5$ K and 10 K. The $(X+X^+)$ and $(X+X^-)$ regions are shaded in blue and orange, respectively. **B**, R_{xy} as a function of V_g and T at $V_b = 0.88$ V.

opposite Lorentz force when it's bound to two electrons in the electron layer.

Figure 3A shows Hall density, n_H , at $T = 1.5$ K and 10 K along $V_b = 0.88$ V which cuts through regions of positive trions, excitonic insulator, and negative trions. The dashed lines are the expected density of holes (blue) and electrons (orange) in respective layers, evaluated from the device capacitances. At 10 K, trions are ionized and n_H traces the expected Hall density. At 1.5 K, n_H deviates from the hole density as the system enters the positive

References:

- [1] D. Jérôme, T.M. Rice & W. Kohn, Excitonic Insulator, Phys. Rev. 158, 462–475 (1967).
- [2] X. Liu, K. Watanabe, T. Taniguchi, B. I. Halperin & P. Kim, Quantum Hall drag of exciton condensate in graphene. Nat. Phys. 13, 746–750 (2017).
- [3] P. X. Nguyen, L. Ma, R. Chaturvedi, K. Watanabe, T. Taniguchi, J. Shan & K.F. Mak, Perfect Coulomb drag in a dipolar excitonic insulator. Science 388, 274–278 (2025).
- [4] P.X. Nguyen, R. Chaturvedi, Ligu Ma, P. Knuppel, K. Watanabe, T. Taniguchi, K. F. Mak & J. Shan, An equilibrium trion liquid in atomic double layers; Science 390, 304–307 (2025).
- [5] R. Chaturvedi, P. X. Nguyen, P. Knuppel, K. Watanabe, T. Taniguchi, K. F. Mak & J. Shan, Trion Hall effect in electron-hole double layers, arXiv:2606.18647.

Bandwidth-Tuned Mott Transition and Superconductivity in Moiré WSe₂

CNF Project Number: 2633-18

Principal Investigator(s): Jie Shan, Kin Fai Mak

User(s): Yiyu Xia, Zhongdong Han, Yichi Zhang

Affiliation(s): LSchool of Applied and Engineering Physics, Laboratory of Atomic and Solid State Physics; Cornell University

Primary Source(s) of Research Funding: Department of Energy, National Science Foundation, Air Force Office of Scientific Research, Gordon and Betty Moore Foundation

Contact: jie.shan@cornell.edu, kinfai.mak@cornell.edu, yx579@cornell.edu, zh352@cornell.edu, yz2662@cornell.edu

Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator System (NPGS), Angstrom E-Beam Evaporator, SC4500 Odd/Even-Hour Evaporator, Oxford 81/82 RIE, YES Asher, Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, Dicing Saw - DISCO

Abstract:

The emergence of semiconductor moiré materials provides a new platform to simulate the Hubbard model, which is believed to capture the essential physics of high- T_c superconductivity. In this study, by tuning the twist angle of two WSe₂ layers, we reach the intermediate-coupling regime, where we observe a range of high- T_c phenomenology. By further tuning an out-of-plane electric field, we modify the band structure and find that the superconducting T_c rises as the Mott insulator weakens, peaking near the electric-field-driven Mott transition.

Summary of Research:

The Hubbard model is believed to capture the essential physics of high- T_c superconductivity [1-3]. In cuprates, the bandwidth W and the interaction strength U are comparable, placing these materials in the moderate-correlation regime [3]. Despite its simple appearance, the model is extremely difficult to solve in this regime, which makes a controllable quantum simulator highly desirable. Semiconductor moiré superlattices provide one such platform, realizing the model on a triangular lattice [4]. Although hallmarks such as the Mott insulator have been observed for years, superconductivity was demonstrated only recently [5,6]. In this study, by tuning the relative twist angle in two WSe₂ layers, we reach a regime close to that of the cuprates and observe a series of high- T_c phenomena.

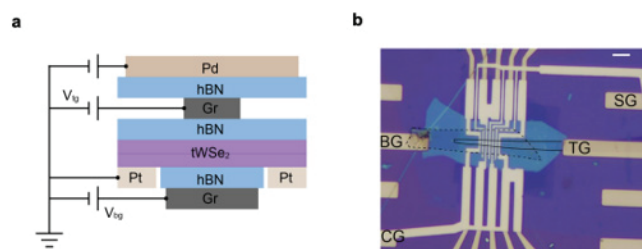


Figure 1. A, Schematic of the dual-gated device structure. B, Optical microscope image of a 4.6° tWSe₂ device. The scale bar is 4 μm .

Figure 1 shows the device structure and an optical image of a twisted WSe₂ bilayer (tWSe₂) device. The encapsulated twisted bilayer is transferred onto prepatterned platinum electrodes; a top and bottom gate form a dual-gated geometry that independently control the hole filling factor ν (in moiré density) and the out-of-plane electric field E . The latter creates an energy offset between the two layers, thereby modifying the moiré band structure.

Figure 2 shows the resistance as a function of ν and E for devices with twist angle ranging from 2.1° to 4.7°. The twist angle sets the moiré period and therefore controls the bandwidth relative to and correlation strength. The correlated insulators at $\nu = 1, 1/3$ and $1/4$ are observed at small twist angles ($\leq 4.3^\circ$); they weaken as the angle increases, showing that the correlation effect weakens. Superconductivity emerges near 3.5° around $E = 0$ mV/nm and shifts to higher E field following the Mott insulator. We focus on the 4.6° device, for which U and W are comparable which is most relevant to the physics of cuprates.

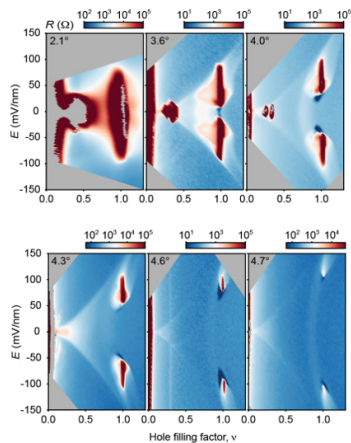


Figure 2: Twist-angle-dependent resistance as a function of filling factor ν and electric field E for devices with twist angle from 2.1° to 4.7° at $T = 50$ mK and $B = 0$ T.

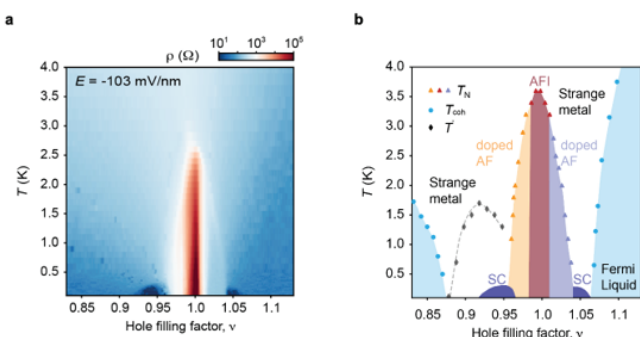


Figure 3: A, Longitudinal resistivity ρ as a function of filling factor ν and temperature T at $E = -103$ mV/nm for the 4.6° device. B, Phase diagram constructed from A. It exhibits an AF insulator (AFI) (red), electron-doped AF insulator (yellow), hole-doped AF insulator (purple), superconductors (SC) (dark blue), strange metal and Fermi liquid (light blue) with corresponding temperature scales T_N , T_{coh} and T' (symbols).

Figure 3 shows ρ_{xx} as a function of ν and temperature T at a fixed electric field $E = -103$ mV/nm and the phase diagram constructed from the data. At $\nu = 1$, we find an antiferromagnetic Mott insulator: the resistivity rises with $T < T_N \approx 3.5$ K, with the Néel temperature T_N defined at the local resistivity minimum. Correspondingly, the magnetic susceptibility shows a cusp at T_N with a Curie–Weiss behavior above T_N . Small doping yields an antiferromagnetic metal with a small Fermi surface, for which a local minimum can be identified in the ρ – T curve at T_N . Further doping produces a superconducting dome on each side of the insulator. The metallic states adjacent to the superconductor are strange metals, showing T -linear resistivity from 100 mK to 10 K. A Fermi liquid is recovered at large doping. The resulting phase diagram is reminiscent to that of the high- T_c cuprates.

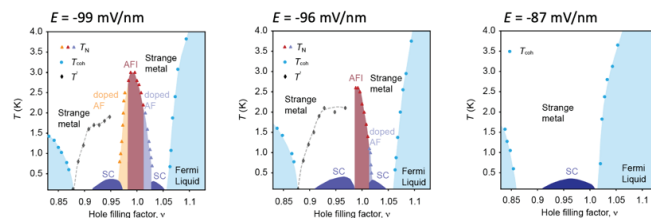


Figure 4: Temperature-filling phase diagrams constructed at different electric fields for the 4.6° device.

Figure 4 shows the phase diagrams constructed at different electric fields. E tunes the band structure, and thereby effectively tunes the Fermi velocity around filling $\nu = 1$ as well as the strength of the Mott insulator. As shown in Figure 2, a metal-to-insulator transition is observed near $\nu = 1$ at a critical field of about -92 mV/nm. As E increases from the insulating side, the phase diagram evolves continuously: the antiferromagnetic insulator weakens, with T_N falling and the doped antiferromagnetic regions shrinking, whereas the superconducting domes expand and T_c increases. Beyond the transition, the insulator vanishes and only one superconducting dome is observed. The highest T_c occurs near the critical field, close to the E -field-driven Mott transition.

Conclusions and Future Steps:

We observe in moiré WSe_2 a phase diagram resembling that of the high- T_c cuprates. The tunability of this platform offers insight into the high- T_c problems and supports the view that superconductivity is closely related to the Mott transition. As a next step, we will characterize the properties of the novel states. For example, tunnelling experiments in the superconductor and the doped AF state will tell us the gap size of the superconductor, and whether the doped AF state exhibits a pseudogap as seen in the cuprates.

References:

- [1] Hubbard, J. Proceedings of the Royal Society A 276, 238–257 (1963).
- [2] Anderson, P. W. Science 235, 1196–1198 (1987).
- [3] Lee, P. A., Nagaosa, N., Wen, X.-G. Reviews of Modern Physics 78, 17–85 (2006).
- [4] Kennes, D. M. et al. Nature Physics 17, 155–163 (2021).
- [5] Xia, Y. et al. Nature 637, 833–838 (2025).
- [6] Guo, Y. et al. Nature 637, 839–845 (2025).

Investigating the Impact of an External Electric Field on Thermal Behavior

CNF Project Number: 2758-19

Principal Investigator(s): Zhiting Tian

User(s): Amelia Schaeffer, Aloyse Maille

Affiliation(s): Sibley School of Mechanical and Aerospace Engineering

Primary Source(s) of Research Funding: Office of Naval Research

Contact: zt223@cornell.edu, afs97@cornell.edu, aam299@cornell.edu

Research Group Website: <https://ztgroup.org/>

Primary CNF Tools Used: ABM Contact Aligner, SUSS MA6-BA6 Contact Aligner, SC4500 Odd-Hour Evaporator, Glen 1000 Resist Strip, Everbeing EB-6 DC Probe Station

Abstract:

As electronics continue to scale to smaller dimensions and increased power densities, understanding how electric fields impact the thermal properties of materials becomes important for accurate thermal budgeting. In this work, we fabricate structures to study how thermal properties of hexagonal boron nitride (h-BN) change when a cross-plane electric field is applied to the material. Microscale metal-insulator-metal structures with Ti/Au contacts were fabricated using dry transfer, contact photolithography, electron-beam evaporation, and liftoff processing. Measurement and analysis of the thermal conductivity and thermal boundary conductance of the h-BN flakes during DC electrical biasing is ongoing.

Summary of Research:

To perform thermal measurements, a lateral h-BN flake dimension of at least 80 μm is desirable, and thicker flakes are selected to help limit the influence of the interfaces on thermal measurements. Bulk samples are not used since a single-crystal domain is necessary to eliminate the effect of grain boundaries. Additionally, the voltage sources required to apply significant electric fields across bulk crystals are significantly more hazardous than those that can be used to apply high fields when a thin crystalline flake is used. Compared to typical 2D material flakes used for device fabrication, these flakes have much larger lateral dimensions ($\sim 100\text{ }\mu\text{m}$ x $\sim 100\text{ }\mu\text{m}$) and are thicker (100 nm to 100 nm). This,

combined with the electrode dimensions, allows us to utilize contact photolithography to pattern our electrodes, a technique not typically used for 2D flakes.

Mask design, mask writing, and photolithography dose testing were all performed as initial steps in the device development process. To make a wafer of devices, the bottom electrodes are patterned, metal is deposited, and liftoff is performed. A bottom electrode thickness of 40 nm (10 nm Ti adhesion layer, 30 nm Au) was used to minimize the step edge the flake needed to be draped over while still giving a mechanically robust bottom electrode for further processing and testing. The minimization of the step edge helps to prevent air bubble formation and flake delamination during device fabrication. After the bottom electrode is set, standard dry transfer techniques are used to precisely place h-BN flakes onto the bottom electrode. Then, the top electrode is patterned on top of the flake, and deposition and liftoff are repeated. Sonication cannot be used at any step once the flakes are placed, as it can lead to delamination. An example of a fully fabricated device is shown in Figure 1.

Iteration on this general process was necessary to ensure repeatable and high-quality results. The initial wafer of devices run showed contaminants on the flake that affected the top electrode, and atypical aging of the gold used for both the top and bottom electrodes was observed. An oxygen plasma resist strip and a more aggressive substrate clean prior to processing resolved these two issues, respectively.

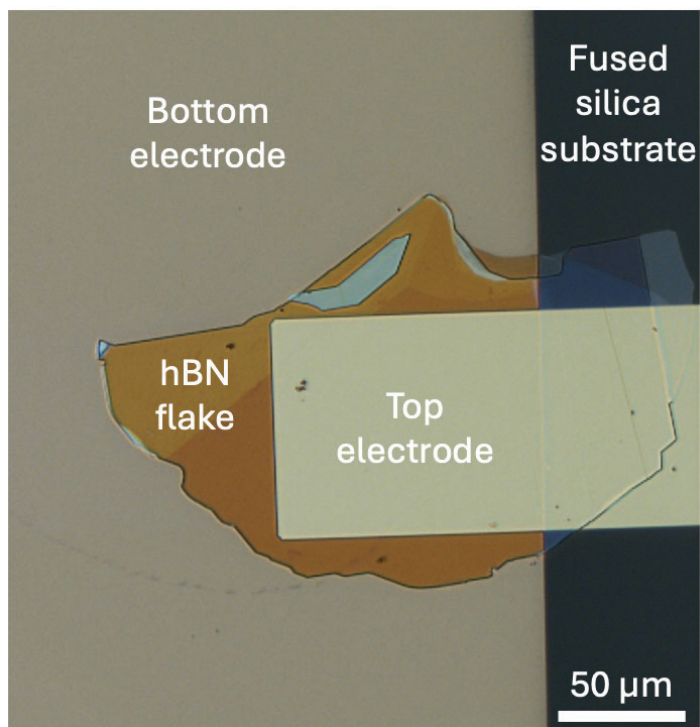
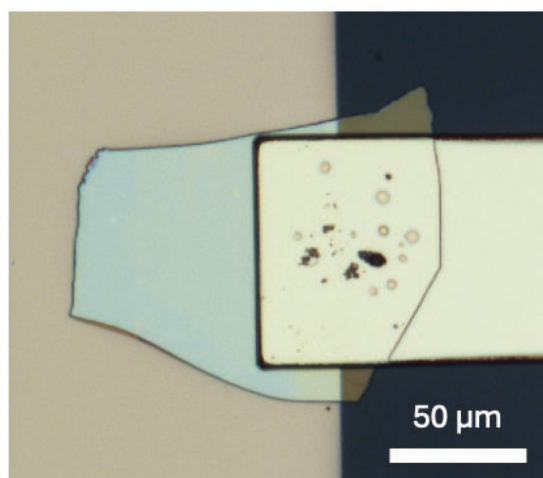


Figure 1: An optical microscope image of a fully-fabricated device with structures labelled for clarity. Both the top and bottom electrodes are Au with a Ti adhesion layer; but the difference in electrode color in the microscope image is due to the different thicknesses of Au used in the top and bottom electrodes.

Conclusions and Future Steps:

A repeatable and effective fabrication method has been developed for these devices that ensures well-defined contacts and clean surfaces. These devices are now undergoing thermal measurements while fields are applied, and future steps will be informed by the experimental results obtained from these measurements.

First Wafer



Second Wafer

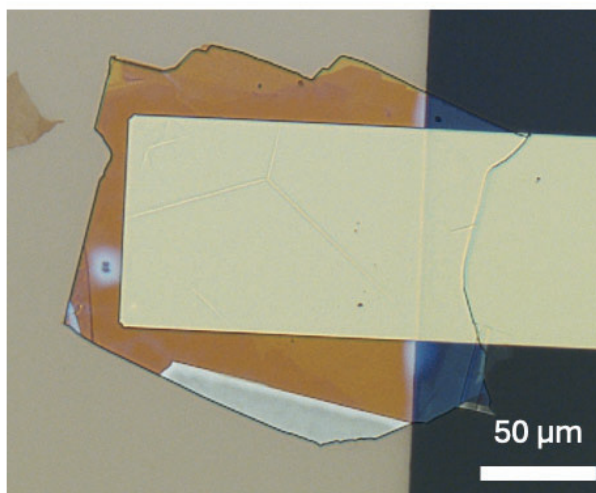


Figure 2: Two optical microscope images showing a device on the first wafer fabricated without additional cleaning steps and a device on the second wafer where more robust substrate cleaning and an oxygen plasma clean immediately prior to top electrode deposition helped to eliminate residues present on the first wafer.

Thin-Film Deposition for Surface Characterization Studies for Superconducting Radio Frequency Cavity Application

CNF Project Number: 2779-19

Principal Investigator(s): Matthias Liepe

User(s): Nathan Sitaraman

Affiliation(s): Cornell Laboratory for Accelerator-based Sciences and Education, Cornell University

Primary Source(s) of Research Funding: The U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams

Contact: mul2@cornell.edu, nss87@cornell.edu

Website: <https://physics.cornell.edu/matthias-liepe>

Primary CNF Tools Used: AJA Sputter Deposition 1 & 2

Abstract:

Superconducting radio-frequency (SRF) cavities are a key component of particle accelerators (with applications ranging from fundamental physics research to synchrotron X-ray sources, to e-beam microscopy and lithography) and are also being developed for applications in dark matter detection and quantum computing. We are developing next-generation surface treatments to enhance the performance of niobium superconducting surfaces. By using facilities at the CNF, we investigate the effect of metallic doping on the niobium surface. We highlight our recent success in growing Nb₃Al superconducting alloys and ZrO₂ passivation layers.

Summary of Research:

We used CNF's AJA sputter deposition tools to deposit zirconium on niobium samples for ZrO₂ passivation layer development. Continued progress on this work has led to some of the highest-quality passivation layers demonstrated so far on a superconducting substrate. Additionally, we used the same tools to deposit aluminum on niobium samples for Nb₃Al layer growth. An Nb₃Al sample we grew maintained superconductivity in an RF field of over 80mT, making Nb₃Al just the third superconducting material to reach this threshold.

Conclusions and Future Steps:

We plan to continue optimizing our successful Nb₃Al and ZrO₂ layer recipes, while also returning to earlier work on Nb-Zr alloy formation.

References:

[1] <http://arxiv.org/abs/2606.10144>

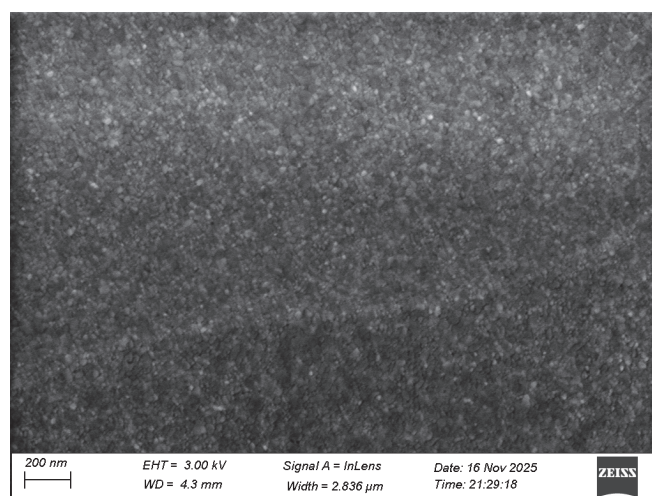


Figure 1: SEM image of ZrO₂-passivated Nb surface, showing a continuous and crystalline ZrO₂ layer.

Enhancement of Laser Plasma Driven Ion Acceleration Using Structured Si Targets on Air-bridged SiO₂ Membranes

CNF Project Number: 2979-21

Principal Investigator(s): Gennady Shvets

User(s): Samyabrata Mukherjee

Affiliation(s): School of Applied and Engineering Physics, Cornell University

Primary Source(s) of Research Funding: Carbon Ion Radiation Therapy (E903324) & NSF project: "Interaction of Ultra-Intense Laser Pulses with Structured Targets in the Multi-Petawatt Regime" (E71-8417)

Contact: gshvets@cornell.edu, sm2575@cornell.edu

Website: <http://shvets.aep.cornell.edu>

Primary CNF Tools Used: JEOL 6300, SC4500 Evaporator, Unaxis 770 Deep Si Etcher, PlasmaTherm Versaline Deep Si Etcher, SUSS MA6-BA6 Contact Aligner, Oxford 82 Etcher, Oxford PECVD, KLA P7 Profilometer, Zeiss Supra SEM, Heidelberg Mask Writer DWL-2000, Hamatech Mask Processor, E-beam and Photolithography Spin Coaters, Resist Hot Strip Bath, Hamatech Wafer Processor, Anatech Resist Strip, FilMetrics

Abstract:

We study the acceleration of heavy ions generated by the interaction of high-power ultrashort laser pulses with structured silicon targets. We compare the yield of heavy ions produced by laser pulses incident on 1 micron-thin air-bridged silicon oxide membranes with the yield from structured silicon metasurfaces resting on similar membranes. Experiments carried out at the ALEPH laser facility in Colorado State University reveal that we obtain a greater flux of higher energy ions from the structured targets compared to the flat foil. Simulations reveal that this enhancement is due to the generation of significantly more energetic electrons during the laser's interaction with structured targets. Such high charge/flux heavy ion beams may have applications in diverse areas including cancer therapy and high-flux neutron generation.

Summary of Research:

Ultrashort, high intensity pulsed lasers have enabled the creation of tabletop ion accelerators which rely on a driving electron component and the resulting electric field created by charge separation. A typical mechanism involves target normal sheath acceleration (TNSA) where a laser beam incident on a solid thin foil target creates an electron sheath on the rear of the target which generates highly energetic ions [1]. The incident laser pulse generates hot electrons which form a charge separation field due to the target's capacitance. At the rear surface, this field is strong enough to ionize atoms, and it accelerates the ions in a direction normal to the surface.

We seek to enhance the flux and energy of the ions produced from thin foils in the standard TNSA scheme

by using nanostructured Si targets resting on air-bridged $\sim 1 \mu\text{m}$ thick SiO₂ membranes (see Fig. 1a). A laser pulse polarized perpendicular to the gap between the Si structures will draw electrons out of the Si blocks into the trench (see Fig. 1a) and accelerate them via direct laser acceleration to relativistic energies which are far greater than the energies obtained in traditional TNSA, leading to a stronger sheath electric field. The thinness of the SiO₂ membrane serves a key purpose where it prevents broadening of the sheath field while maintaining the accelerated electrons at a high temperature. We prepared both Si metasurfaces and gratings with different periods (0.6 μm and 1.2 μm) and prepared unstructured foils as control targets. We also prepared gratings oriented in the wrong direction compared to the laser polarization to check the polarization dependence of the ion-acceleration scheme.

Our targets are produced at the CNF using CMOS compatible processes (see Fig. 1b). We use a buried oxide silicon on insulator wafer and deposit 3 μm SiO₂ on the handle layer to be used as a hard mask for the handle layer etch. We carry out e-beam lithography on PMMA spun on the device layer and evaporate Al₂O₃ on the PMMA after development. The PMMA is then lifted off in acetone and the remaining Al₂O₃ acts as a hard mask for the anisotropic etching of the device silicon layer in the Unaxis 770 using a modified Bosch process recipe. We remove any remaining Al₂O₃ in Al etch and remove polymer coatings on the Si structure sidewalls using EKC polymer strip. The SiO₂ on the handle layer is then patterned via backside aligned photolithography on the MA6 mask aligner followed by etching in the Oxford 82. Finally, the substrate below the Si arrays is etched on the Unaxis 770 using the standard Bosch process.

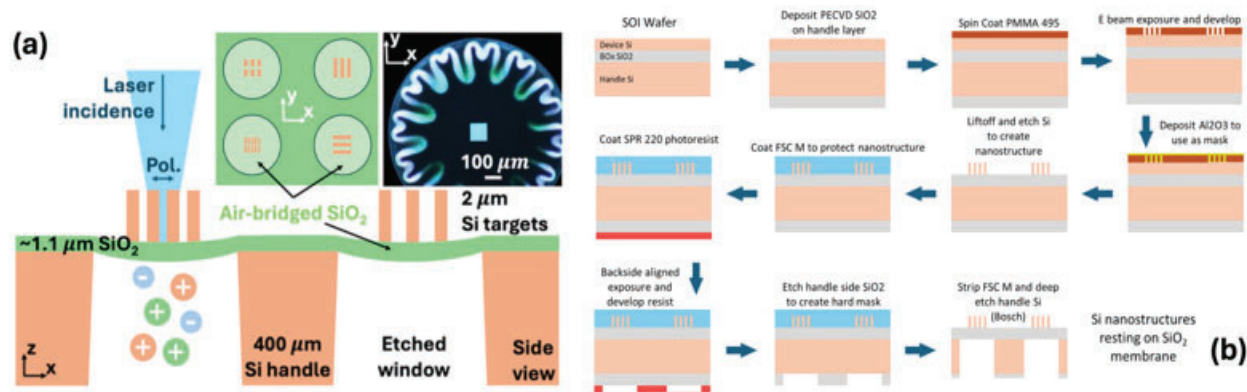


Figure 1: (A) Schematic of the targets and laser incidence with the top right inset showing a dark field micrograph of a Si nanostructure array on a $\sim 1 \mu\text{m}$ SiO_2 membrane. (B) Fabrication process flow.

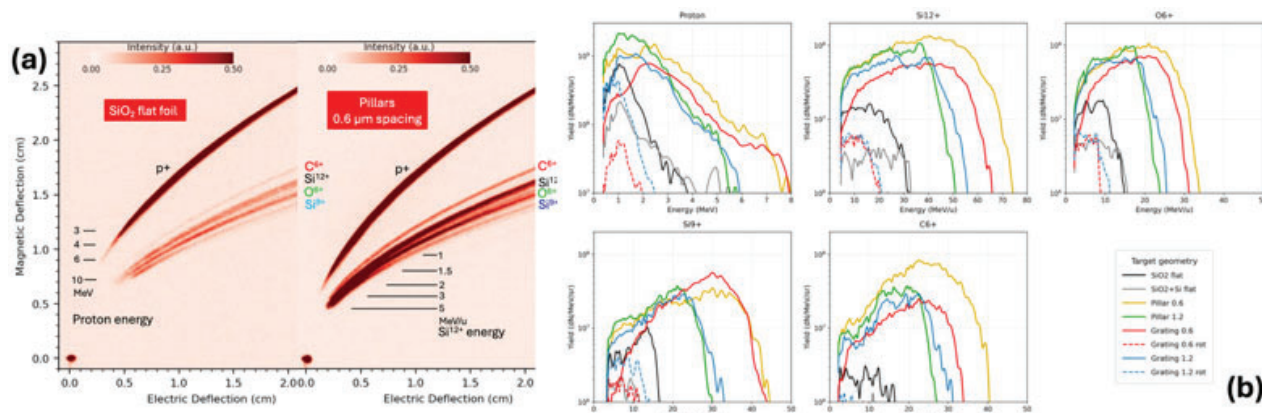


Figure 2: (A) Image plates from a TPS showing traces corresponding to positively charged ion species and a X-ray spot. (B) Spectrum for various positively charged ions obtained from different target types.

We perform our experiments at the ALEPH laser facility in Fort Collins, Colorado where a 400 nm , ~ 50 femtosecond laser deposits $\sim 4 \text{ J}$ of energy in a $\sim 2 \mu\text{m}$ diameter focal spot on our targets leading to intensities of $\sim 2.5 \times 10^{21} \text{ W/cm}^2$. The energies of the ions generated are measured using a Thompson Parabola spectrometer (TPS) and phosphor image plates which are then scanned using a 635 nm laser scanner. Scans of two image plates comparing shots on unstructured SiO_2 foil with $0.6 \mu\text{m}$ spacing Si metasurfaces on similar foil are shown in Fig. 2a. The structured targets produce significantly higher flux and higher energies for various positively charged ion species. Using the geometry and electric and magnetic fields in the TPS, we can fit various ion species to the traces obtained on the image plate and find H^+ , Si^{12+} , Si^{9+} , O^{6+} , and C^{6+} , among others. We compare the yields and energies for these various ion species from different targets in Fig. 2b and find that the metasurfaces and gratings with $0.6 \mu\text{m}$ spacing provide the highest yields and energies while the foils and the rotated gratings with the “wrong” alignment have the lowest yields.

Conclusions and Future Steps:

We have demonstrated a scheme to enhance the acceleration of protons and massive ions from nanostructured Si targets on thin, air-bridged SiO_2 membranes fabricated using CMOS compatible processes. The CMOS-compatible fabrication process lends our scheme to easier translation to industrial settings as well as greater control over target geometry compared to standard nano-wire targets. In the future we plan on running our experiments with additional diagnostics and modified geometries to accelerate other massive ions from Au or W films layered on our targets.

References:

- [1] Roth, M. & Schollmeier, M. Ion Acceleration—Target Normal Sheath Acceleration. CERN Yellow Rep. 231 Pages (2016) doi:10.5170/CERN-2016-001.231.

Development of Josephson Spectroscopy for Low-dimensional Materials

CNF Project Number: 2998-22

Principal Investigator(s): Valla Fatemi

User(s): Luojia Zhang, Andrew Pierce

Affiliation(s): Cornell Applied and Engineering Physics and Physics

Primary Source(s) of Research Funding: Aref and Manon Lahham Faculty Fellowship and Kavli Foundation

Contact: vf82@cornell.edu, lz282@cornell.edu, atp66@cornell.edu

Website: <https://fatemilab.aep.cornell.edu/>

Primary CNF Tools Used: Heidelberg MLA, PT770, JEOL 6300, Angstrom-Q, AJA-1 sputterer

Abstract:

Low-dimensional layered materials including graphene exhibit intriguing electrodynamic properties in the THz frequency range, including correlation-driven energy gaps and plasmonic cavity modes. However, these phenomena are difficult to access experimentally because of the mismatch between sample sizes (typically a few to a few tens of microns) and the wavelengths of THz photons (typically a few hundred microns to a few mm). In this project, we made use of Josephson junctions as on-chip photon sources as an alternative route to accessing THz electrodynamics. By fabricating circuits incorporating Josephson junctions and layered materials, we observed plasmonic collective excitations in graphene and demonstrated their hybridization with modes of a proximal superconducting cavity, thus paving the way for studies of hybrid cavity quantum matter.

Summary of Research:

We fabricated circuits in which a Josephson junction is connected in parallel to a graphene heterostructure. The graphene heterostructure includes NbN top and bottom layers which serve both as gates and to define a confined superconducting cavity mode (Fig. 1A). When the Josephson junction is operated in the voltage-biased state, it emits photons that probe the high-frequency loss of the graphene heterostructure. The high-frequency loss in the circuit is in turn encoded in the DC current across the Josephson junction as required by energy conservation. Thus, by measuring the DC current-voltage characteristic of the Josephson junction, we can probe high-frequency response in graphene

from approximately 10 to 190 GHz.

The loss measured for an NbN/graphene/NbN device, expressed as the real part of the input impedance $\text{Re}(Z_{\text{in}})$, is shown as a function of frequency and of gate voltage (proportional to carrier density) in Fig. 1B. Numerous peaks and dips in the spectrum correspond to different cavity modes of the multi-layered structure, including modes of the superconducting cavity (nearly-vertical features) and plasmon modes of graphene (those that shift with gate voltage). Notably, avoided crossings between modes are visible at 93 and 170 GHz (Fig. 2). These features indicate strong light-matter coupling (hybridization) between different modes in the structure, which raises the possibility of engineering hybrid cavity-matter ground states and degrees of freedom in cavities based on low-dimensional materials.

Conclusions and Future Steps:

Our approach to defining cavities raises the possibility of controlling the effective dielectric function of electrons in low-dimensional materials like graphene. Such engineered dielectric functions serve to modify electronic interactions and have been proposed as a route toward realizing novel correlation-driven ground states. However, cavity-induced ground states are generally expected to be fragile, likely requiring measurements at sub-Kelvin temperatures. The approach to spectroscopy developed to this project is thus ideally suited to probing such novel ground states, as it imposes heat loads on devices that are orders of magnitude smaller than for comparable optics-based THz spectroscopy methods.

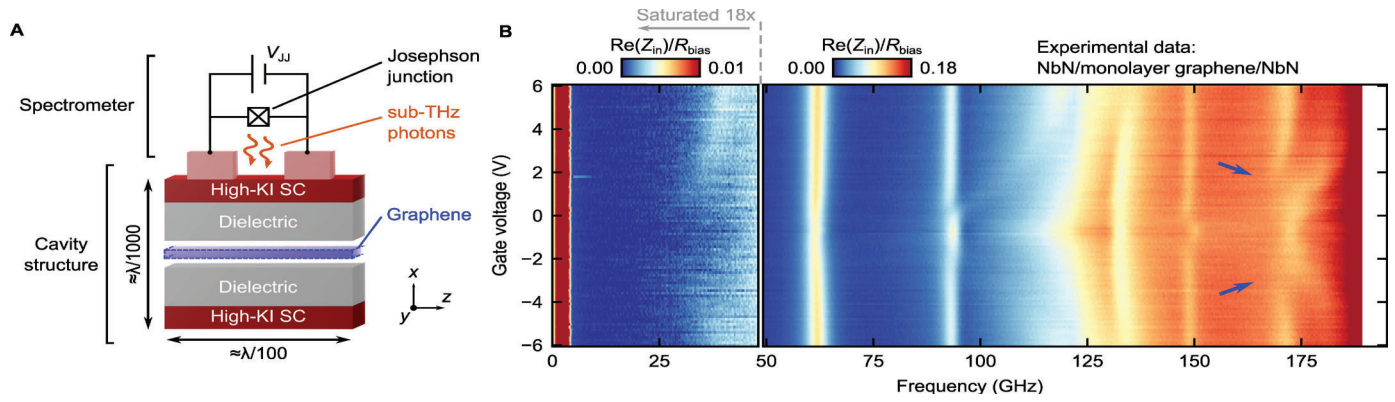


Figure 1: (A) Schematic of device geometry in which a Josephson junction acts as a photon emitter connected to an NbN/ graphene/NbN heterostructure. (B) Measured loss, expressed as $\text{Re}(Z_{\text{in}})$, of an NbN/graphene/NbN device as a function of frequency and gate voltage exhibiting numerous resonant modes. Blue arrows highlight an avoided crossing near 170 GHz.

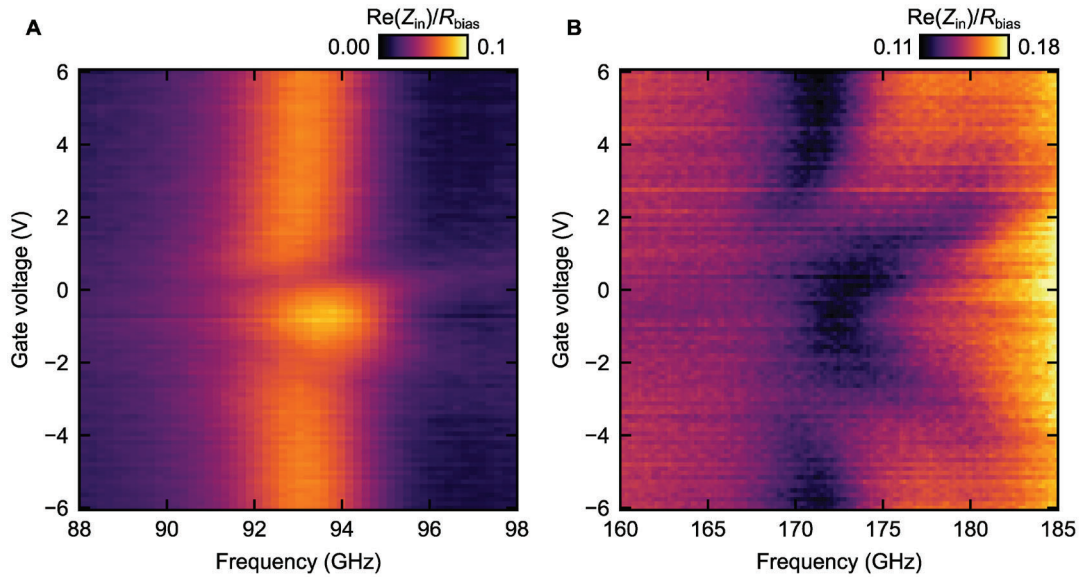


Figure 2: Zoom-in on avoided crossings from Fig. 1B near 90 GHz (A) and 170 GHz (B).

Sensing SiGe-related Superconductor and Dielectric Material Microwave Loss via Flip Chip

CNF Project Number: 2998-22, 311723

Principal Investigator(s): Valla Fatemi

User(s): Haoran Lu, Kushagra Aggarwal

Affiliation(s): Applied and Engineering Physics, Cornell University

Primary Source(s) of Research Funding: AFOSR, Kavli Foundation

Contact: vf82@cornell.edu, lhl2396@cornell.edu, ka543@cornell.edu

Website: <https://fatemilab.aep.cornell.edu/>

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, DWL2000, PT770, ABM contact aligner, SC4500 Even-Hour Evaporator, AJA-1, DISCO dicing saw, Oxford 81, RTA

Abstract:

We developed a flip-chip-based technique that can probe the loss tangent of the target dielectric material, or the complex conductance and surface oxide loss tangent of the target superconductor thin film. We remark that this procedure is fabrication-free for the target material; thus, it can extract the intrinsic microwave loss. This approach establishes a fast-turnaround benchmarking protocol for novel materials, where loss is not accessible via conventional on-chip resonator methods. Ge/SiGe heterostructures are essential to hybrid semiconductor-superconductor devices, such as the Andreev spin qubit—a leading prospective platform for scalable quantum computing. High microwave loss in SiGe-related dielectric materials and contact superconductors remains a major bottleneck. We applied the flip-chip-based technique to study the source and potential mitigation methods in a series of SiGe-related materials.

Summary of Research:

Sensor fabrication:

The sensor fabrication includes SU-8 patterning and resonator defining. To sense the loss of the target film, the sensor must be a few microns away from the target film, with an uncertainty less than half a micron. In this project, we use 4 μm SU-8 pillars, with the whole patterning flow achieved within CNF. The SU-8 pillars are defined on niobium or tantalum thin films, where we further pattern high-quality-factor superconducting resonators. A quick optical microscope and profilometer check is performed to ensure the height and location of SU-8 pillars are within tolerance.

Target chip preparation:

The target film involved in this study includes Nb films (for benchmarking the baseline performance), SiGe-related dielectric materials, and superconductor thin films. We diced the SiGe heterostructures into a size that fits the flip-chip sensor. They underwent different treatments, such as oxygen etch to remove the quantum well (QW), HF treatment to deplete the QW, and (niobium) platinum deposition and annealing to form a (Nb)PtSiGe alloy.

Measurement:

The target dielectric materials and superconductor thin films are flipped onto the sensor and cooled down in cryostats. We measure the quality factor of the sensing resonators and analyze the performance of individual target chips accordingly.

Conclusions and Future Steps:

We demonstrated a flip-chip-based loss sensing scheme and applied it on a Ge/SiGe material series. In the coming months, we will use the sensing scheme to study multiple novel materials.

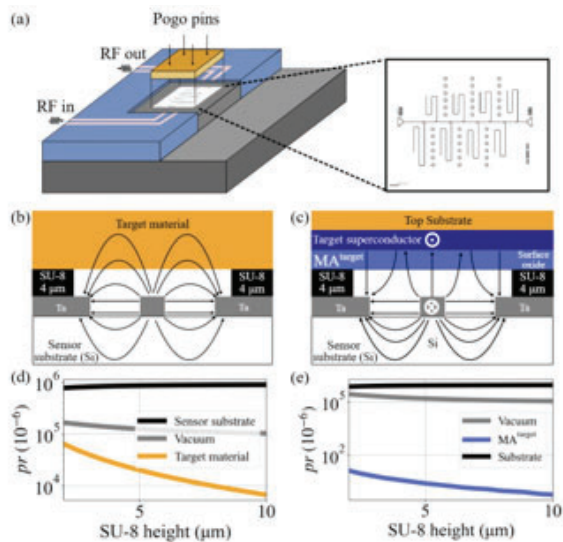


Figure 1: a) Schematic of the flip-chip-based sensor. b) Dielectric material sensing scheme. c) Superconductor thin film sensing scheme. d) Participation ratio of the dielectric target material versus SU-8 pillar height. e) Participation ratio of the target superconducting thin film surface oxide versus SU-8 pillar height.

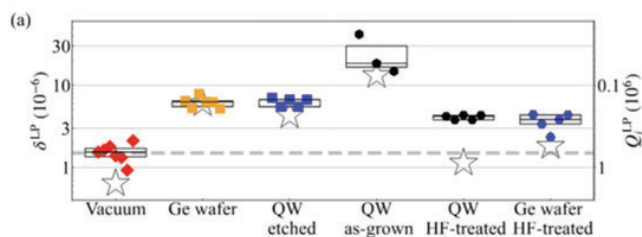


Figure 2: Boxplot of low power ($\langle n \rangle < 10$) intrinsic loss (dots) and high power ($\langle n \rangle > 10^6$) intrinsic loss (stars) for dielectric materials measured by the flip-chip-based sensor.

Fabrication of Waveguides for Biophotonics and Resonators for Quantum Photonics

CNF Project Number: 3008-22

Principal Investigator(s): Professor Pablo A. Postigo

User(s): Christopher (Christer) Everly, Martin Sanchez, Jaymit Surve, Sophia Korono

Affiliation(s): Institute of Optics, University of Rochester

Primary Source(s) of Research Funding: University of Rochester Startup Fund, URA Award 2023-2024 from University of Rochester

Contact: ppostigo@ur.rochester.edu, ceverly@ur.rochester.edu, msanch23@ur.rochester.edu, jsurve@ur.rochester.edu, skorono@ur.rochester.edu

Website: <https://postigolab.com>

Primary CNF Tools Used: JEOL 9500, E-beam Spin Coaters, Olympus MX-50 Microscopes, Oxford 82, Oxford 100, PT770 RIE, Oxford Cobra ICP, Plasma Therm Tikachi HDP-CVD, Oxford PECVD, Primaxx Vapor HF Etcher, Yes EcoClean Asher, Yes Asher, Filmetrics systems, Zeiss Ultra SEM, Zeiss SEM Supra, Veeco AFM, Disco Dicer Saw

Abstract:

Our group investigates nanophotonic devices for biosensing, quantum sensing, and single photon sources. The geometries we're currently focused on are waveguides for coupling to neurons, Mach-Zehnder Interferometers (MZI) for biosensing, dual photonic crystal (PhC) nanobeams for room-temperature single phonon quantum sensing, and Circular Bragg Cavities (CBGs) for Purcell enhancement of single photon emitters. Recent research achievements include measurement of resonances in the dual nanobeam cavities, and validation of a custom axisymmetric Finite-Difference Frequency-Domain solver used to inverse design the CBGs. Preliminary simulations and measurements are currently underway for the biophotonic devices.

Summary of Research:

Newest users were successfully trained on the Oxford PECVD, Photolithography, and Oxford 82 to facilitate the fabrication of future biophotonic devices. Simulations of waveguide geometries for biosensors based on MZIs are on-going, with fabrication to follow. Coupling measurements between in-house fabricated fiber probes and waveguides (a neuron surrogate) are currently underway.

Successful fabrication of suspended single and dual PhC nanobeams is routine due to thorough process development. Notably, anisotropic etches are achieved using a Hydrobromic Acid (HBr) inductively coupled plasma (ICP) etch, instead of the sulfur hexafluoride and oxygen (SF_6/O_2) chemistry frequently seen in literature for silicon etches. The PhC nanobeams are

released with vapor hydrogen fluoride (HF) etching to create the suspended structures without any stiction. Extensive lab work have resulted in the first successful resonance measurements with good agreement between simulations.

Fabrication of CBGs are also promising; a slight ellipticity was recently measured due to the pattern rastering behavior of the JEOL 9500. This was only found due to successful fabrication of high optical quality factor (Q) of the CBGs. The measurements were in good agreement with the custom FDTD solver, validating the implementation – a paper detailing the process is in progress.

Conclusions and Future Steps:

An initial waveguide geometry for the MZI will necessitate a fabrication at Cornell Nanoscale Facility (CNF) with some process development expected. A suitable geometry for neuron and axon growth on chip will also be investigated and potentially fabricated at CNF. The functioning PhC nanobeams will be placed under vacuum in attempts to measure an optomechanical signal. The CBGs will be characterized before distribution to collaborators for single photon emitter integration.

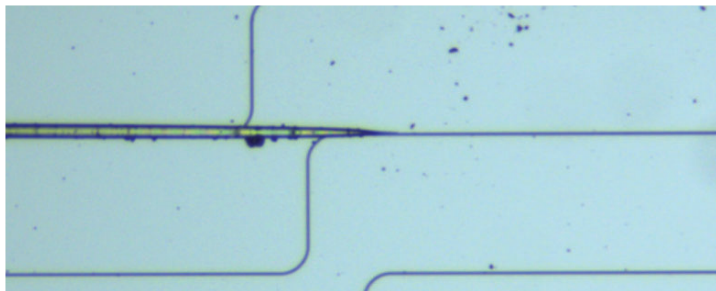


Figure 1: A fiber probe brought close to a waveguide for coupling measurements.

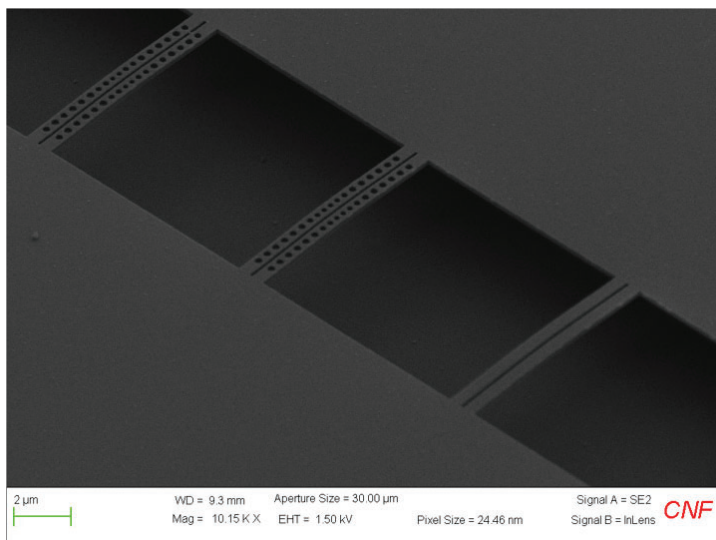


Figure 2: Fabricated free standing dual photonic crystal optomechanic nanobeam cavities.

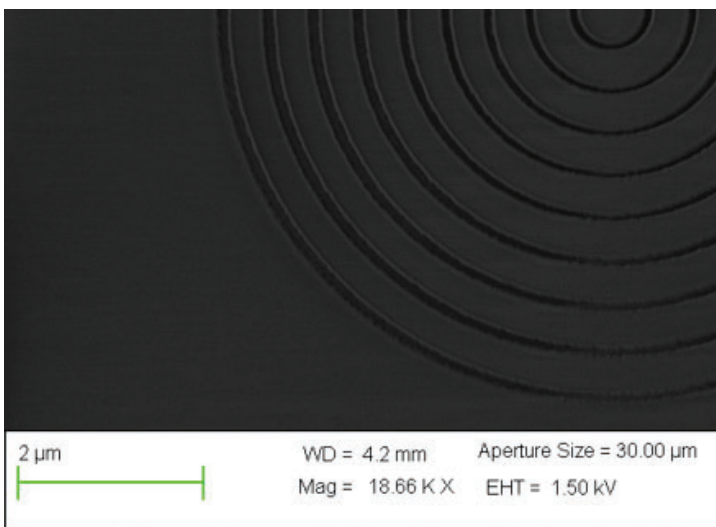


Figure 3: A fabricated CBG with some vertical roughness visible from the top-down raster.

References:

- [1] Martin Sanchez, Christer Everly, Lukas Weituschat, et al. "Inverse design of bullseye cavities using tandem neural networks," Proc. SPIE 14143, Photonics for Quantum 2026, 141430K (2026); <https://doi.org/10.1117/12.3111281>
- [2] Hekmati, R., Hadden, J. P., Mathew, A., Bishop, S. G., Lynch, S. A., & Bennett, A. J. "Bullseye dielectric cavities for photon collection from a surface-mounted quantum-light-emitter," Scientific Reports 13(1), 5316 (2023). <https://doi.org/10.1038/s41598-023-32359-0>
- [3] Weituschat, L.M., Castro, I., Colomar, I. et al. "Exploring regenerative coupling in phononic crystals for room temperature quantum optomechanics," Scientific Reports 14, 12330 (2024). <https://doi.org/10.1038/s41598-024-63199-1>
- [4] Schliesser, A., Rivière, R., Anetsberger, G. et al. "Resolved-sideband cooling of a micromechanical oscillator," Nature Physics 4, 415–419 (2008). <https://doi.org/10.1038/nphys939>

Resistivity Scaling in PdGa Nanowires

CNF Project Number: 3032-22

Principal Investigator(s): Judy Cha

User(s): Mingqi Zhong, Nghiep Khoan Duong

Affiliation(s): Department of Materials Science and Engineering, Cornell University

Primary Source(s) of Research Funding: Semiconductor Research Corporation JUMP 2.0 SUPREME

Contact: jc476@cornell.edu, mz668@cornell.edu

Website: <https://cha.mse.cornell.edu/>

Primary CNF Tools Used: Zeiss Supra SEM, Nabity NPGS Nanometer Pattern Generator System, Oxford 81 RIE, SC4500 Even and Odd-Hour Evaporator, Westbond 7400A Ultrasonic Wire Bonder, Veeco Icon AFM

Abstract:

Topological semimetals possess topologically protected surface states that suppress carrier backscattering, and in contrast to traditional metals, are predicted to possess enhanced conductivity at reduced dimensions. PdGa is predicted to host topologically protected Fermi arcs, and its relatively low bulk resistivity ($23 \mu\Omega\cdot\text{cm}$) motivates its study as a potential post-copper interconnect material. In this work, we synthesize PdGa nanowires with diameters between 20 and 150 nm using thermomechanical nanomolding (TMNM). High angle annular dark field scanning transmission electron microscopy (HAADF-STEM) confirms single-crystal $P2_13$ structure in the nanowire core, while electron energy loss spectroscopy (EELS) reveals a Ga-deficient shell attributed to wet etch damage during device processing. We observe the resistivity of the molded nanowires to be higher than bulk, but also that the resistivity decreases with decreasing wire diameter within batch. We attribute the elevated resistivity to the Ga vacancies induced during wet etching. However, because resistivity decreases on a per-batch basis, we hypothesize that surface states are still partially intact.

Summary of Research:

To fabricate PdGa nanowires, we use thermomechanical nanomolding, in which bulk PdGa is extruded through a nanoporous anodic aluminum oxide (AAO) mold under heat and pressure. Following KOH etching of the mold, nanowires are detached via sonication and dropcast onto substrates, yielding wires with diameters spanning 20–150 nm. Atomic-resolution HAADF-STEM imaging of freestanding nanowires confirms a single-crystal $P2_13$ structure in the wire core. STEM-EELS elemental mapping, however, reveals

a core-shell structure: the core is stoichiometric PdGa, while the shell is deficient in gallium, which we attribute to damage introduced during the wet etch step.

Four-point probe devices are fabricated on individual nanowires via e-beam lithography using equipment at the CNF. Low-temperature transport measurements indicate metallic behavior with a residual resistance ratio (RRR) of ~ 1.2 , indicating that resistance is dominated by surface scattering rather than phonon scattering. Across five fabrication batches, measured resistivity is higher than bulk ($23 \mu\Omega\cdot\text{cm}$) but decreases with decreasing wire diameter within each batch. This suggests that surface-state conduction pathways remain intact despite the shell of Ga vacancies. Notably, absolute resistivity varies appreciably from batch to batch, which we interpret as reflecting differences in etch damage. Line resistance is presently well above that of copper across the measured size range (roughly an order of magnitude higher at 20 nm).

Conclusions and Future Steps:

Our results show that PdGa nanowires exhibit elevated resistivity relative to bulk, which we attribute primarily to gallium vacancies introduced by etch damage during device fabrication. The decreasing resistivity with decreasing diameter on a per-batch basis suggests that the underlying surface-state transport channel remains intact despite this damage. Next steps focus on quantifying etch-induced damage directly on bulk PdGa crystal. In parallel, theoretical calculations modeling the effect of Ga vacancies on transport are underway.

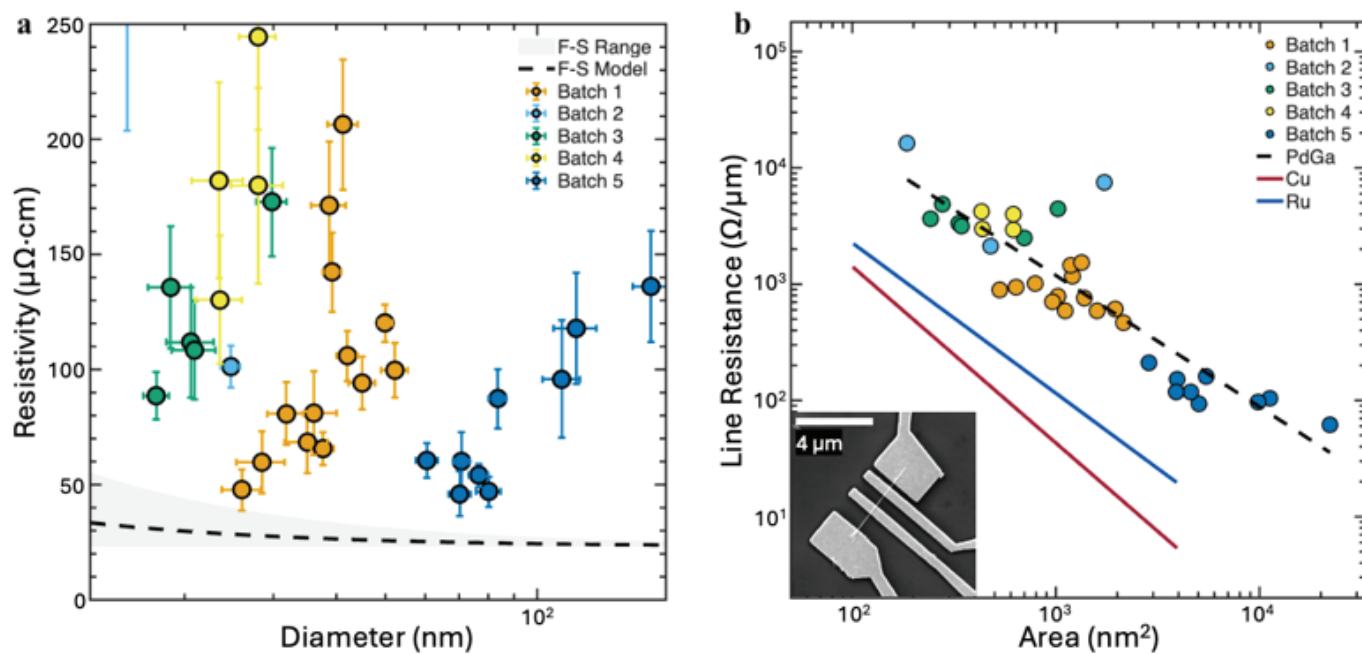


Figure 1: (a) diameter-dependent resistivity of five different batches of PdGa nanowires. (b) Cross-sectional area-dependent line resistance scaling of nanowires. Inset: a representative four-point probe device.

Kinetically Controlled Memory in Nanoconfined Ionic-Electronic Memtransistors

CNF Project Number: 3064-23

Principal Investigator(s): Yu Zhong

User(s): Kaushik Chivukula

Affiliation(s): Materials Science and Engineering, Cornell University

Primary Source(s) of Research Funding: Cornell Startup Funding

Contact: yz2833@cornell.edu, kc836@cornell.edu

Website: <https://zhong.mse.cornell.edu>

Primary CNF Tools Used: Resist Spinners, Heidelberg DWL2000, ABM Mask Aligner, SC4500 E-Beam Evaporators, HMDS Oven, Oxford 81/82 RIE, Oxford FlexAL, Ellipsometry

Abstract:

Solvated ions confined within biological nanochannels regulate information processing and memory, motivating efforts to replicate such mechanisms for energy-efficient neuromorphic hardware. Artificial synaptic devices, including two-terminal nanofluidic memristors [1,2] and three-terminal electrolyte-gated transistors [3-5], have demonstrated history-dependent conductance modulation and diverse neuromorphic functionalities. However, memory in existing systems originates from specific ion-ion[1], ion-channel[1,2], or ion-host [3-5] interactions, making retention strongly dependent on material choice and chemical environment. Here, we establish a distinct, kinetically driven route to memory by confining electrolytes within an ultrathin crown-ether polymer sandwiched between two semiconducting molybdenum disulfide (MoS_2) monolayers. The confining polymer, along with a single-sided electrolyte opening, imposes an extended ion-diffusion pathway, kinetically retarding ion transport and enabling history-dependent conductance modulation of the underlying MoS_2 channel (Fig 1). Critically, in highly polar solvents where strong ion-solvent interactions suppress hysteresis in the non-confined device, nanoconfined devices show significant hysteresis that persists across cation identity and electrolyte concentration, establishing confinement as a route to achieve memory beyond previously established ion-environment interactions. Additionally, independent drain and gate-driven Na^+ motion enables electrical tuning of ion relaxation dynamics and memory timescales within a single device (Fig 2), allowing emulation of both basic synaptic functions (Fig 3) as well as higher-order heterosynaptic plasticity (Fig 4). These results establish nanoconfinement in three-terminal ionic-electronic heterostructures as a general platform for achieving hysteretic ion transport, controlling memory timescales and enabling biomimetic, multi-terminal neuromorphic devices.

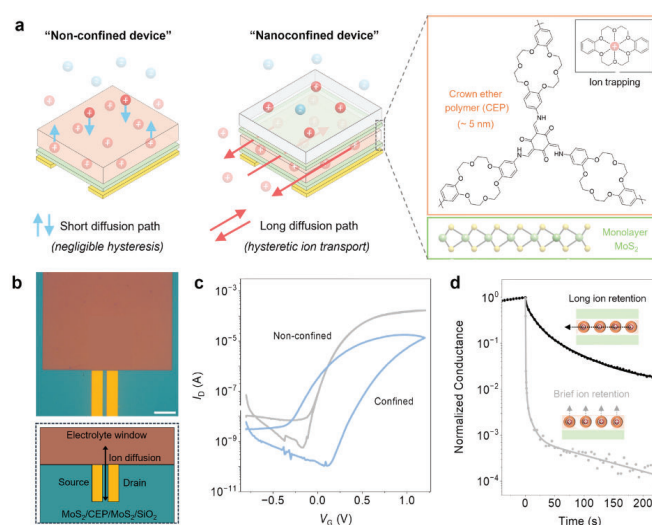


Figure 1: Ion dynamics governed by confinement geometry

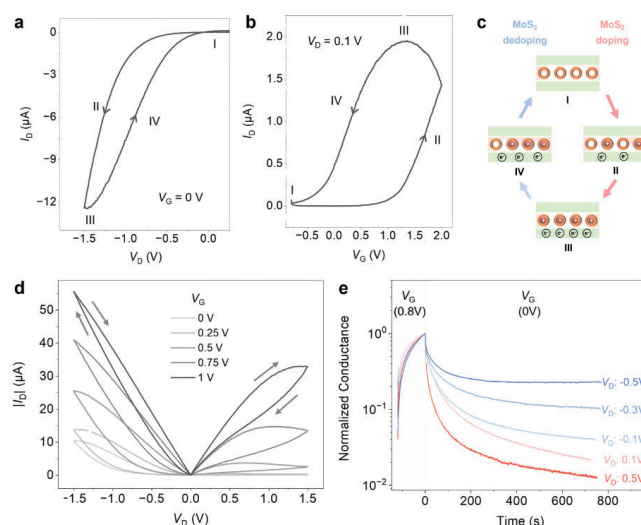


Figure 2: Electrical characteristics of nanoconfined devices

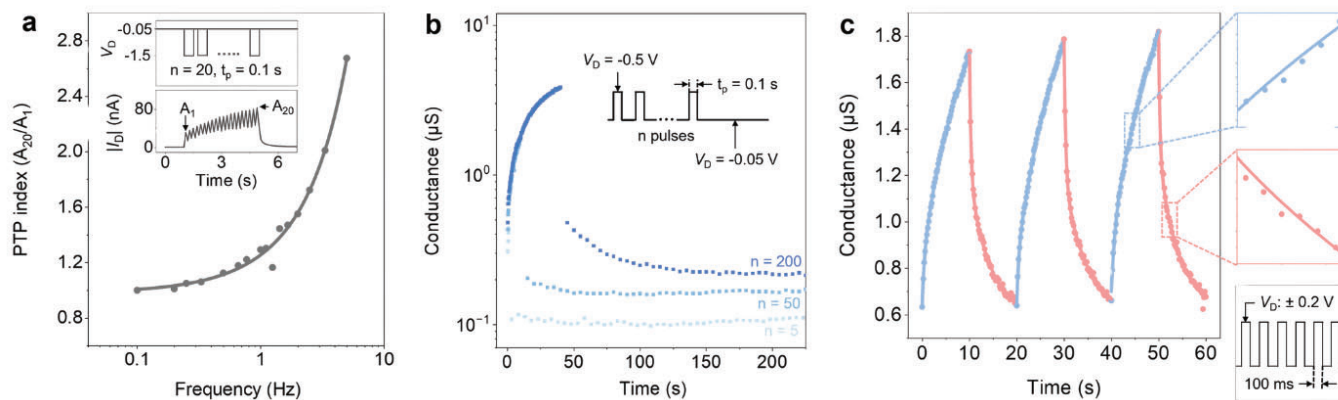


Figure 3: Synaptic plasticity functions emulated using drain bias.

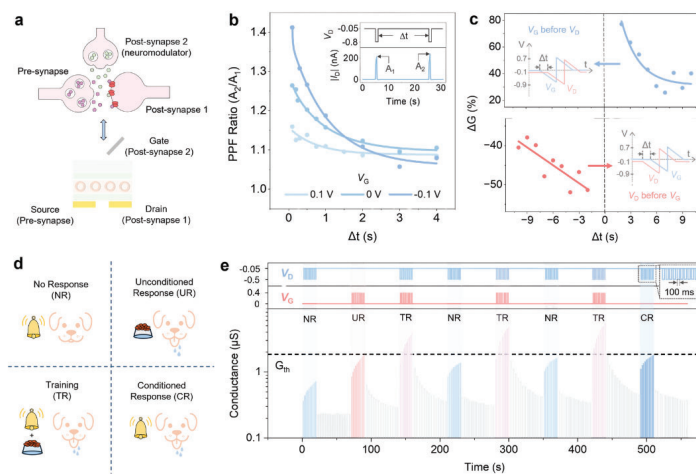


Figure 4: Heterosynaptic plasticity enabled by multi-terminal device operation

Summary of Research:

We establish geometric nanoconfinement as a kinetically driven route to ionic memory that does not require strong ion-ion, ion-host or ion-channel interactions. An extended ion-diffusion pathway enables robust hysteresis across solvents, cations and electrolyte concentrations, while independent drain and gate biases control ion relaxation and memory timescales, allowing replication of both basic synaptic functionalities and higher-order heterosynaptic plasticity.

Conclusions and Future Steps:

In conclusion, we demonstrate that memory can arise from kinetically retarded ion transport rather than from specific ion-ion, ion-channel or ion-host interactions. Geometric confinement within a three-terminal MoS₂-polymer-MoS₂ heterostructure imposes an extended, lateral ion diffusion pathway that enables history-dependent conductance modulation of the underlying MoS₂ channel across different solvents, cations and electrolyte concentrations, including conditions in which unconfined devices show negligible hysteresis.

Independent drain- and gate-driven ion motion further enables electrical control over ion relaxation dynamics and memory timescales, replicating both traditional synaptic functionalities and higher-order heterosynaptic plasticity. These findings establish nanoconfinement as a general strategy for engineering hysteretic ion transport and tunable memory in multi-terminal ionic–electronic synaptic devices.

References:

- [1] Robin, P.; Emmerich, T.; Ismail, A.; Niguès, A.; You, Y.; Nam, G.-H.; Keerthi, A.; Siria, A.; Geim, A. K.; Radha, B.; Bocquet, L. *Science* 2023, 379, 161–167.
- [2] Xiong, T.; Li, C.; He, X.; Xie, B.; Zong, J.; Jiang, Y.; Ma, W.; Wu, F.; Fei, J.; Yu, P.; Mao, L. *Science* 2023, 379, 156–161.
- [3] Zhou, H.; Chivukula, K.; Fang, Q.; Wang, K.; Ren, X.; Garudapalli, A.; Liang, C.; Tian, J.; Butler, S.; Liang, A.; Xu, J.; Zhang, H.; Xie, S.; Yeo, J.; Zhong, Y. *ACS Mater. Lett.* 2026, 8, 205–212.
- [4] Yao, B.; Li, J.; Chen, X.; Yu, M.; Zhang, Z.; Li, Y.; Lu, T.; Zhang, J. *Adv. Funct. Mater.* 2021, 31, 2100069.
- [5] Xu, K.; Lu, H.; Kinder, E. W.; Seabaugh, A.; Fullerton-Shirey, S. K. *ACS Nano* 2017, 11, 5453–5464.

Aluminum Resonator and Josephson Junction Fabrication Process Development for Superconducting Qubits

CNF Project Number: 3116-23

Principal Investigator(s): Zhiting Tian

User(s): Simon Shi, Aloyse Maille

Affiliation(s): Sibley School of Mechanical and Aerospace Engineering, Cornell University

Primary Source(s) of Research Funding: Fellowship

Contact: zt223@cornell.edu, ls795@cornell.edu, aam299@cornell.edu

Primary CNF Tools Used: Electron-beam Lithography, Optical Lithography, AJA sputtering systems, ICP Etcher

Abstract:

This report summarizes process development for Al resonators and Josephson junctions for superconducting qubits. The work focused on fabricating aluminum thin-film device structures on sapphire substrates, with emphasis on resonator patterning, Josephson junction electrode definition, multilayer alignment, and process reproducibility. A major part of the effort involved troubleshooting fabrication steps such as resist coating, lithography exposure, pattern transfer, etching, resist removal, structural alignment and surface cleaning to obtain clean and well-defined Al patterns. Resonator structures were successfully patterned on Al-on-sapphire samples, providing a foundation for future microwave characterization. In parallel, Josephson junction electrode layouts were designed and developed to support controlled bottom-electrode definition, oxidation, and top-electrode integration. These efforts establish an initial fabrication framework for superconducting qubit components and provide guidance for future process optimization.

Summary of Research:

This project focused on developing fabrication processes for superconducting qubit components, specifically Al microwave resonators and Al Josephson junction structures on sapphire substrates. Aluminum is widely used in superconducting quantum circuits because it can form both superconducting electrodes and a native aluminum oxide tunnel barrier, while sapphire provides a low-loss insulating substrate suitable for microwave devices.

The first part of the work focused on Al resonator fabrication. Aluminum films on sapphire substrates were patterned into resonator structures using lithography and dry etching. The goal was to produce clean and continuous Al features with good pattern fidelity and minimal process-related defects. As shown

in Figure 1, resonator patterns were successfully defined on an Al-on-sapphire chip, demonstrating the feasibility of the fabrication workflow. A significant amount of troubleshooting was required to improve the final pattern quality, including optimization of resist processing, lithography conditions, etching parameters, and cleaning steps. Optical inspection was used throughout the process to evaluate pattern definition, identify defects, and guide process adjustments.

The second part of the work focused on Josephson junction process development. Josephson junctions are key nonlinear circuit elements for superconducting qubits, but their fabrication requires precise control of electrode geometry, tunnel barrier formation, and alignment between multiple lithography steps. The



Figure 1: Fabricated Al-on-sapphire resonator chip showing patterned resonator structures on the top surface.

junction process was developed around Al bottom and top electrodes, with controlled oxidation used to form the aluminum oxide barrier. Figure 2 shows the designed Josephson junction electrode feature from CAD, including the bottom and top electrode regions and the intended overlap area for junction formation.

A major challenge in the Josephson junction process was achieving reliable alignment between different

lithography layers. Since the final junction area depends on the overlap between electrodes, even small offsets can affect device yield and reproducibility. Process trials were therefore used to evaluate alignment strategies, mark visibility, resist thickness, exposure conditions, and overlay accuracy. Additional troubleshooting was

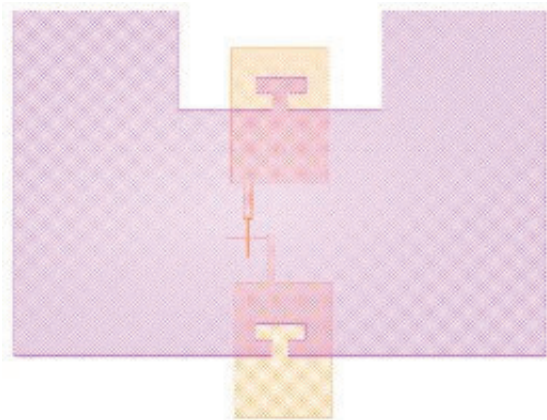


Figure 2: CAD layout of the Josephson junction electrode design.

also performed during etching, resist removal, and surface preparation steps to obtain cleaner electrode features and more reliable pattern transfer.

Conclusions and Future Steps:

This work established a preliminary fabrication process for Al resonators and Josephson junctions on sapphire substrates for superconducting qubit applications. Resonator patterns were successfully fabricated, and Josephson junction electrode designs and key process steps were developed. Troubleshooting across lithography, etching, resist removal, surface cleaning, and alignment helped improve pattern quality and process reproducibility.

Future work will focus on improving overlay accuracy, optimizing oxidation and etching conditions, and reducing fabrication variability. The next steps will also include device performance testing.

Nonvolatile Switching of Magnetism via Gate-Induced Sliding in Tetralayer Graphene

CNF Project Number: 3125-23

Principal Investigator(s): Kenji Yasuda

User(s): Daniel Brandon, Lujin Min, Yiwen Ai, Kyle Nadel, Peter Golemis, Akshat Gandhi, Zhen Yang

Affiliation(s): School of Applied and Engineering Physics, Department of Physics, Cornell University

Primary Source(s) of Research Funding: Lab Start-up Fund, Department of Energy

Contact: kenji.yasuda@cornell.edu, db923@cornell.edu

Research Group Website: <https://sites.google.com/view/kenjiyasuda>

Primary CNF Tools Used: Heidelberg MLA 150, Zeiss Supra SEM, Nabity Nanometer Pattern

Generator System (NPGS), Angstrom Load lock E-beam Evaporator, Oxford PlasmaLab 80+ RIE System (Oxford 81)

Abstract:

Within multilayered 2D van der Waals systems the stacking degree of freedom is an important parameter which often directly controls the electronic properties of the material. This is especially relevant in multilayered graphene systems, where the metastable rhombohedral stacking order has been reported to host exotic electronic states which are absent in the more commonly found Bernal stacking arrangement. In this work, we will show the ability to in situ control the stacking order via electrostatic gating and therefore switch the ferromagnetism found uniquely in the rhombohedral stacking order on and off [1].

Summary of Research:

When multiple layers of graphene are stacked together, the way in which they are stacked controls the electronic structure. The Bernal stacking order (ABAB), is most commonly found and does not host any exotic correlated states. However, the rhombohedral stacking order (ABCA) instead hosts a variety of exotic phases including a correlation driven quarter metal state which hosts an anomalous Hall effect. The favorability of the stacking order can be controlled via doping and displacement field, which can be independently controlled via electrostatic gating in a dual gated architecture.

In nonmagnetic conductive material, the Hall resistance, R_{yx} , varies linearly with respect to the field, named the ordinary Hall effect (OHE). In ferromagnets, which host finite magnetic moment at zero field, an additional contribution occurs even at zero magnetic field, dubbed the anomalous Hall effect (AHE). In certain graphene systems, like rhombohedral stacked graphene, this

uniquely correlation and valley driven AHE can be observed under certain conditions. We fabricate Hall bar devices of multilayered graphene devices, where we can switch the dominant stacking structure between rhombohedral and Bernal thus switching on and off this AHE.

First, we fabricate multiple Hall bar devices, shown in Figure 1. These devices undergo a stacking procedure which allows us to utilize a dual-gated architecture for control over both doping and displacement field, before fabrication to define the main channel and voltage probes. By flowing current along the main channel and measuring the voltage on either side of the channel, we can accurately measure the Hall resistance.

We first confirm the structural switching of our devices by measuring the longitudinal resistance, R_{xx} , versus doping as controlled by the top and bottom gates at almost zero displacement field in Figure 2. As the doping is tuned to and from the most negative corner, a clear difference between the forward and backward directions is observed. This hysteretic behavior is a sign of the structural transition between the rhombohedral and Bernal favored states, which are shown in Figure 2.

Now with a clear hysteretic signal between the rhombohedral and Bernal structures, we can measure the Hall resistance on either side of the transition. As can be seen in Figure 3, the rhombohedral side reveals a clear nonzero R_{yx} contribution even at zero magnetic field which is absent on the Bernal side. This contribution flips sign as the field is applied, revealing magnetic hysteresis, a signature of ferromagnetism

Conclusions and Future Steps:

In this work we have shown the ability to control the stacking order of few layer graphene via a sliding transition between the rhombohedral and Bernal stacking orders tuned electrostatically. Along with this structural sliding transition, we reveal the ability to turn on and off the magnetic state found only in the rhombohedral structure. In the future we hope to expand this structural

control of correlated phases to the other states reported in this structure, such as chiral superconductivity [2].

References:

- [1] D. Brandon et al., Nonvolatile Switching of Magnetism via Gate-Induced Sliding in Tetralayer Graphene, arXiv: 2510.00220
- [2] T. Han et al., Signatures of Chiral Superconductivity in Rhombohedral Graphene, Nature 643, 654 (2025).

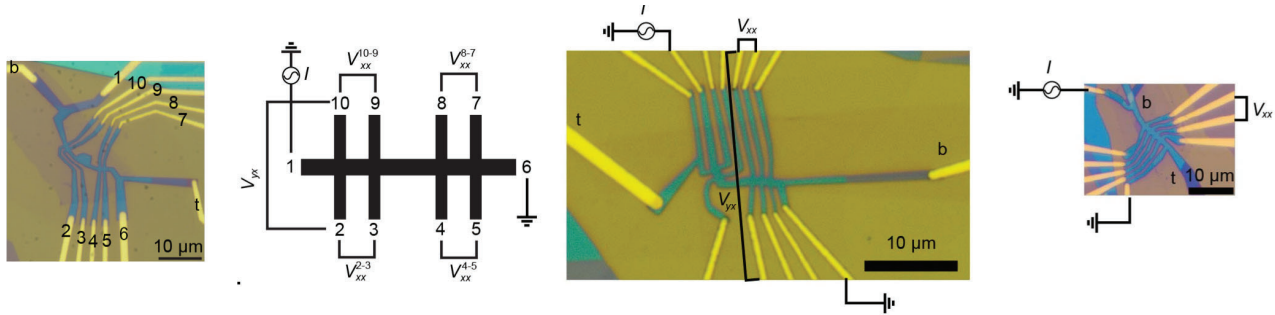


Figure 1: Left - Optical image of device 1, which is measured in Figures 2 and 3. Middle Left - Measurement configuration of device 1. Middle Right - Optical image and configuration of device 2. Right - Optical image and configuration of device 3.

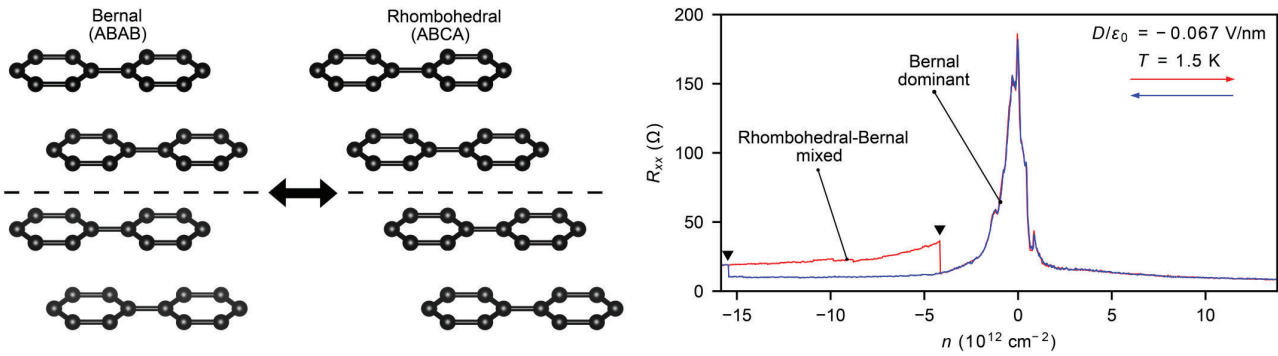


Figure 2: Left - Stacking structure of Bernal and rhombohedral tetralayer graphene respectively. Right - Longitudinal resistance measured versus doping in the forward (red) and backward (blue) directions. A clear difference is observed.

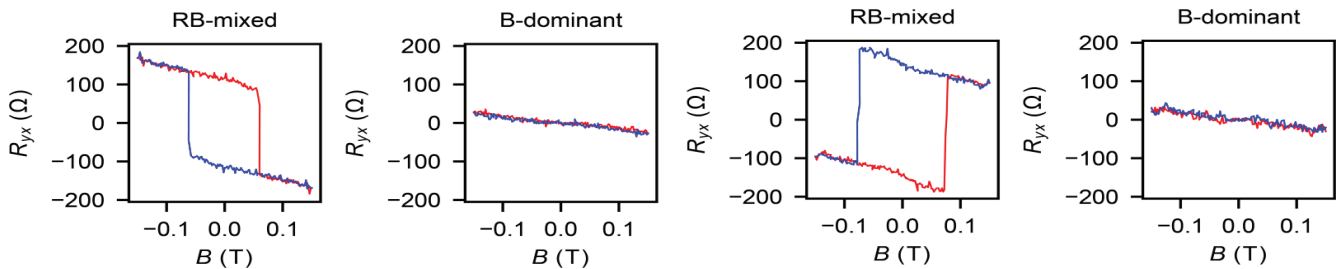


Figure 3: Left and Middle Right - Hall resistance versus magnetic field measured in the rhombohedral-Bernal state.. A clear hysteresis is observed. Middle Left and Right - Hall resistance versus magnetic field measured in the Bernal-dominant state. Only the ordinary Hall effect is seen.

Transport and Scanning Tunneling Microscopy Devices Based on van der Waals Heterostructures

CNF Project Number: 3162-24

Principal Investigator(s): Xiaomeng Liu

User(s): Zhida Liu, Alexander Sanchez, Jiabin Xie

Affiliation(s): Laboratory of Atomic and Solid State Physics, Department of Physics, Cornell University

Primary Source(s) of Research Funding: National Science Foundation, College of Arts and Sciences

Contact: xiaomengliu@cornell.edu, zl2293@cornell.edu, aes444@cornell.edu, jx399@cornell.edu

Research Group Website: <https://www.xiaomengliu.com/>

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, Heidelberg DWL 2000, Zeiss Supra Scanning Electron Microscope, Nabity Nanometer Pattern Generator System, Oxford 81/82 Reactive Ion Etchers, Oxford FlexAL Atomic Layer Deposition System, SC4500 Electron-Beam Evaporators

Abstract:

This report describes three van der Waals device efforts: low-temperature transport in rhombohedral graphene, a twisted ABC graphene device, and a scanning tunneling microscopy (STM)-compatible device. The transport platforms use multiterminal geometries to measure longitudinal and Hall responses, whereas the STM platform preserves a clean, exposed surface for local spectroscopy. CNF lithography, plasma etching, microscopy, dielectric deposition, and metal deposition are central to all three efforts.

Summary of Research:

Our work combines electrical transport with local tunneling spectroscopy to study correlated and topological states in two-dimensional materials. The projects share a fabrication platform based on dry-transferred van der Waals stacks, alignment to pre-patterned markers, plasma etching, and metal deposition. The transport devices remain encapsulated, whereas the STM device must retain electrical connectivity while exposing a clean surface to the tunneling tip.

Project 1: Rhombohedral Graphene Transport

Rhombohedral (ABC-stacked) graphene provides an intrinsically rich platform for correlated-electron physics because its low-energy bands can become narrow and interaction-dominated, while electrostatic gates independently control carrier density and displacement field. In our heterostructures, a nearby twisted transition-metal dichalcogenide stack generates a remote, long-wavelength modulation in the ABC graphene. Combining this engineered periodic potential with the native correlated states of ABC graphene offers

a route to reconstruct the electronic spectrum and explore emergent correlated and topological phases. We fabricate encapsulated heterostructures and pattern them into Hall bars with longitudinal and transverse voltage probes. Four-terminal measurements separate longitudinal resistance from the Hall response, while electrostatic gates tune carrier density and, when applicable, displacement field. Figure 1 shows a completed device after metal liftoff. Before cooldown, we check contact continuity, gate leakage, and channel resistance. At low temperature, multiple probe pairs and forward/reverse sweeps of density, magnetic field, temperature, and DC bias help distinguish intrinsic features from contact mixing, inhomogeneity, or metastability. The CNF-fabricated devices are subsequently measured in a dilution refrigerator.

Project 2: Twisted ABC Graphene Device

Stacking two sets of multilayer rhombohedral graphene one on top of the other at a slight twist angle modifies

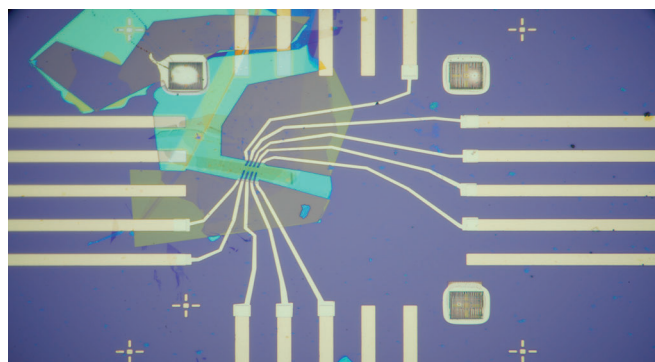


Figure 1: Optical micrograph of the completed multiterminal Hall-bar device after metal liftoff. The central van der Waals heterostructure is connected to multiple longitudinal and transverse voltage probes for low-temperature transport measurements.

the band structure of the graphene, potentially further flattening it. These flat bands can exhibit various quantum states which could be precursor states to those necessary for stable quantum computers. We are exploring different device configurations by varying layer number and twist angle to stabilize these states in twisted rhombohedral graphene heterostructures. By patterning our devices into Hall bars for electronic measurements using the methods heretofore described, we can probe the quantum states of our devices. Figure 2 shows a completed twisted rhombohedral graphene device patterned into a Hall bar geometry for measurement.

Project 3: Direct-Write STM Device

STM requires atomic-scale access to the sample surface, but conventional lithography can leave polymer residue in the scan region. We therefore use a top hBN layer as

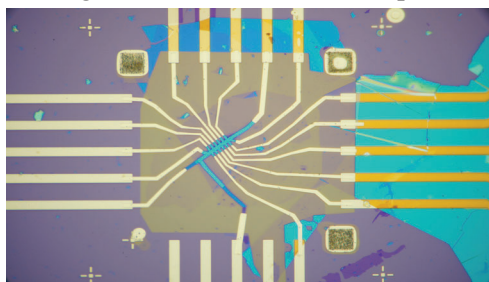


Figure 2: Optical micrograph of a twisted rhombohedral graphene device which has been etched into a Hall bar geometry for transport measurements, using nanofabrication facilities.

a temporary protective cover during fabrication. Direct-write photolithography defines the alignment marks, contact pads, and routing. After completing the electrical structure, we translate the top hBN laterally to expose the active device while preserving the contacts and gate architecture. Graphene on hBN provides a low-disorder platform for local spectroscopy [3], and edge contacts provide robust electrical access [4]. Figure 3 shows the device after hBN displacement. Optical registration locates the exposed window relative to the contacts, and electrical checks confirm continuity and gate isolation. These steps allow the STM tip to approach a clean, electrically tunable region without contacting a metal lead or remaining hBN terrace.

CNF Nanofabrication Workflow

The Heidelberg MLA 150 and DWL 2000, together with photolithography spinners, define direct-write patterns and large alignment features. Fine patterns are written using the Zeiss Supra SEM and Nabity Nanometer Pattern Generator System after resist preparation on the

E-Beam Lithography Spinners. Oxford 81/82 etchers provide CHF_3/O_2 or O_2 plasma processes for mesas and contact edges; the Oxford FlexAL supports dielectric deposition when required; and the SC4500 Even/Odd evaporators deposit contact metals. Microscopy between steps verifies alignment, channel geometry, contact continuity, and the position of the movable top hBN

Conclusions and Future Steps:

The three projects establish complementary routes for probing two-dimensional quantum materials. The rhombohedral-graphene and twisted-ABC platforms enable longitudinal and Hall measurements, while the STM design adds spatially resolved access to an electrically tunable device. Near-term work will complete low-temperature transport characterization, compare contact pairs and sweep directions, and refine hBN displacement to maximize the clean STM-accessible area. We will then evaluate tunneling stability and spectroscopic quality. CNF alignment, etching, deposition, and inspection capabilities remain central to converting assembled flakes into reliable devices.

References:

- [1] Park, H. et al. Observation of fractionally quantized anomalous Hall effect. *Nature* 622, 74-79 (2023).
- [2] Zeng, Y. et al. Thermodynamic evidence of a fractional Chern insulator in moiré MoTe_2 . *Nature* 622, 69-73 (2023).
- [3] Xue, J. et al. Scanning tunnelling microscopy and spectroscopy of ultra-flat graphene on hexagonal boron nitride. *Nature Materials* 10, 282-285 (2011).
- [4] Wang, L. et al. One-dimensional electrical contact to a two-dimensional material. *Science* 342, 614-617 (2013).

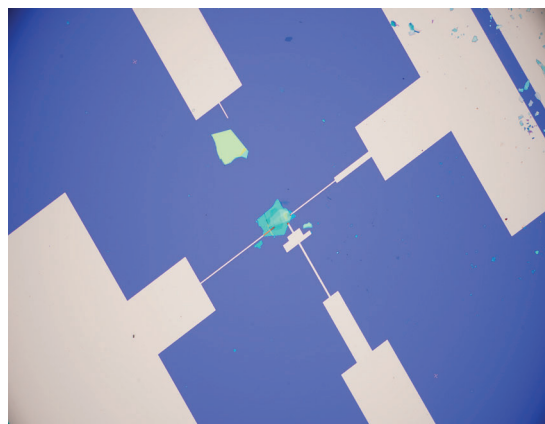


Figure 3: Optical micrograph of the laser-direct-written STM device after lateral displacement of the protective top hBN. The central heterostructure remains electrically connected while an exposed region is made accessible to the STM tip.

Reliable Prepatterned STM Fabrication and Real-Space Imaging of Quantum Hall Quasiparticles

CNF Project Number: 3199-24

Principal Investigator(s): Xiaomeng Liu

User(s): Yiming Sun, Jinghao Deng

Affiliation(s): Laboratory of Atomic and Solid-State Physics, Cornell University

Primary Source(s) of Research Funding: The College of Arts & Sciences, Cornell University, National Science Foundation

Contact: xl956@cornell.edu, ys2289@cornell.edu, jd2353@cornell.edu

Research Group Website: <https://www.xiaomengliu.com>

Primary CNF Tools Used: Heidelberg DWL 2000 Mask Writer , GCA AS200 i-line Stepper, Oxford Plasmalab 81/82 RIE, SC4500 Odd-Hour Evaporator, DISCO Dicing Saw

Abstract:

This report details a novel fabrication methodology that enables the reliable production of scanning tunneling microscopy (STM) prepatterned chips, which subsequently facilitated the direct real-space imaging of individual quantum Hall quasiparticles. By integrating precision photomask design, optimized interfacial metal stacks, and defect-minimized processing, we achieved greater than 95 percent yield in devices capable of targeting sub-5-micron flakes. Leveraging this platform, we utilized scanning tunneling spectroscopy to observe the spatial and spectroscopic fingerprints of quasiparticles in graphene. We successfully resolved the localized electrostatic potentials around charged defects and observed the sequential addition of fractionally charged anyons in the fractional quantum Hall regime.

Summary of Research:

Scanning tunneling microscopy achieves atomic resolution but suffers from an intrinsically small field of view, rendering navigation to specific micron-scale 2D materials slow and prone to tip crashes. Because external localization aids are impractical in extreme cryogenic environments [1, 2], we developed recipes in the Cornell NanoScale Facility for prepatterned chips with integrated registration markers. This resolved the navigation challenge and enabled our subsequent quantum Hall measurements on graphene devices [3].

Critical to this process was precision photomask engineering. Using the Heidelberg DWL 2000, we created quartz photomasks with alignment markers resolvable at 199 nm scales. During lithography, we optimized a bilayer resist system (LOR3A/SPR700) to create STM-specific undercut profiles, producing 800 nm apertures with tapered sidewalls via the GCA i-line

stepper. For the flake-electrode interfaces, we utilized an ultrathin Chromium and Palladium bilayer (3.5 nm Cr / 15 nm Pd) for edge contacts, providing an oxidation-resistant and atomically flat surface essential for tip stability. Finally, a damage-mitigated device release using inverted solvent immersion and predefined dicing minimized edge fractures, yielding chips with greater than 90 percent electrode integrity (Fig. 1-2).

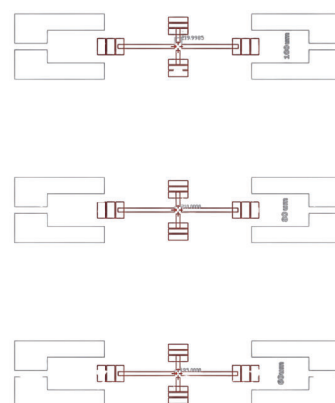


Figure 1: STM_v3 mask design showing 3-micron alignment markers used to eliminate coordinate drift and target microscale 2D materials.

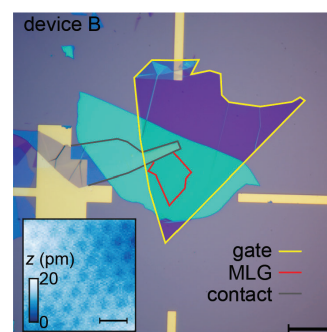


Figure 2: Optical micrograph of a complete graphene-based 2D device fabricated on an STM prepattern chip.

These highly reliable platforms allowed us to perform scanning tunneling spectroscopy on pristine graphene and hexagonal boron nitride heterostructures under high magnetic fields. While quantum Hall quasiparticles have traditionally been studied via macroscopic transport measurements, identifying and imaging them in real space has been a persistent challenge. Our prepatterned chips allowed the STM tip to accurately target the active device region and probe incompressible quantum Hall states.

By mapping the local density of states, we focused on localized electrostatic potentials created by charged defects in the hexagonal boron nitride substrate. These defects acted as quantum dots, splitting the energy levels of the Landau orbitals (Fig. 3). We were able to spatially image the discrete wavefunctions of these orbitals.

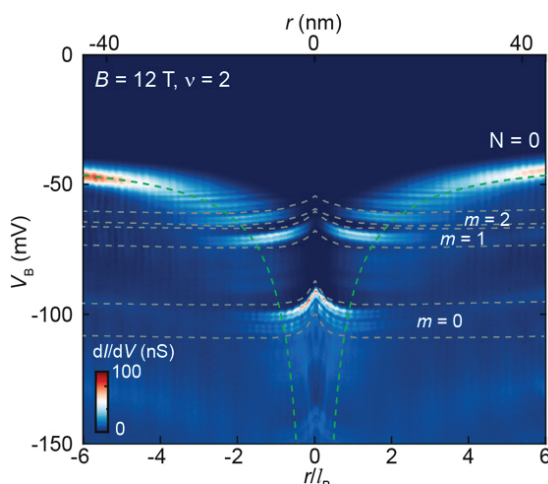


Figure 3: Scanning tunneling spectroscopy maps revealing the discrete energy splitting of Landau orbitals near a localized defect.

Furthermore, by applying this technique to the fractional quantum Hall regime, specifically at one-third filling, we observed unique spectroscopic fingerprints (Fig. 4). Our spectroscopic mapping demonstrated the spatial and energetic signatures of fractionally charged quasiparticles (anyons) becoming trapped by the defect potentials. The experimental data matched theoretical predictions for a three-anyon bound state, providing the first real-space visualization of fractional quasiparticle addition.

Conclusions and Future Steps:

The established CNF fabrication process directly enabled our breakthroughs in resolving the spectroscopic fingerprints of individual quantum Hall quasiparticles in real space. Future work will extend this fabrication methodology to highly air-sensitive quantum materials

via glovebox-compatible integration. Scientifically, we plan to utilize these platforms to explore other exotic fractional quantum Hall states and develop methodologies for the direct real-space manipulation of anyons.

References:

- [1] Li, G., Luican, A. & Andrei, E. Y. Self-navigation of a scanning tunneling microscope tip toward a micron-sized graphene sample. *Rev. Sci. Instrum.* 82, 073701 (2011).
- [2] Liu, X. et al. Visualizing broken symmetry and topological defects in a quantum Hall ferromagnet. *Science* 375, 321–326 (2022).
- [3] Deng, J. et al. Real-space imaging of quantum Hall quasiparticles. Preprint at <https://arxiv.org/abs/2606.25036> (2026).

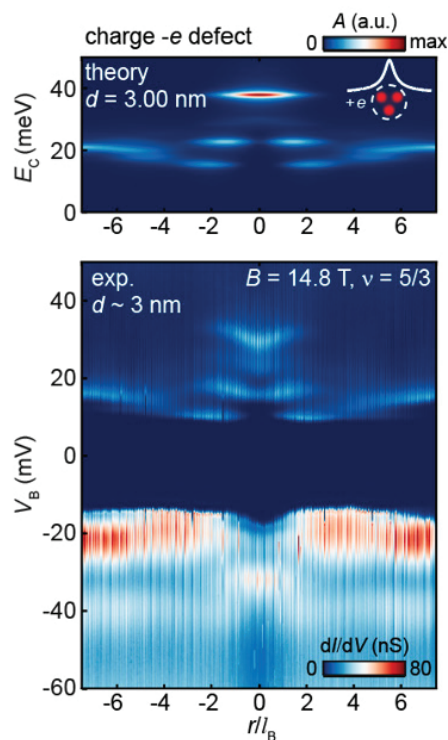


Figure 4: Spectroscopic data at one-third filling of holes demonstrating the sequential addition of three fractional anyons into a bound state.

Sensor Development for Picosecond Timing

CNF Project Number: 3213-24

Principal Investigator(s): Marina Artuso

User(s): Bridget Mack

Affiliation(s): Department of Physics, Syracuse University

Primary Source(s) of Research Funding: National Science Foundation

Contact: martuso@syr.edu, bjmack@syr.edu

Research Group Website: <https://hep.syr.edu/>

Primary CNF Tools Used: DISCO Dicing Saw, Westbond 7400A Ultrasonic Wire Bonder, Everbeing EB-6 Probe Station with Keithley 4200 SMU unit

Abstract:

Future particle detectors will require fast timing capabilities to handle the high luminosities planned for collider experiments. Research and development into ultrafast silicon detectors such as low gain avalanche diodes is needed to reach resolutions on the order of 10 picoseconds. Multiple fabrication parameters, including implantation energy, thickness, and mask area need to be optimized for sensing large quantities of particles in high radiation environments. Several of these design parameters are being tested, with goals to characterize design parameters of low gain avalanche diodes for precision timing applications in high energy particle detectors.

Summary of Research:

The future of particle physics as a field relies on heavy research and development in instrumentation motivated by the physics goals of the next generation of experiments. Proposed future collider experiments boast higher luminosities, meaning – from a detector standpoint – large influxes of particles and radiation over short timescales. The ability to attach a precise time stamp on the order of 10 picoseconds to position or energy measurements becomes crucial, with broad potential to be transformative not only in particle physics instrumentation, but also in other research areas such as medical imaging [1-3].

Low gain avalanche diodes are good candidates for use in both tracking detectors and hybrid calorimeters including layers with high granularity and timing resolutions. The added gain layer at the junction creates a high electric field, leading to charge multiplication and an amplified signal with a sharp rise time, thus yielding

good timing resolution [4]. Multiple parameters—including active area, thickness, and gain—must be tailored to the specific granularity, radiation hardness, and acceptance requirements of a given detector system. Ten 4-inch wafers with arrays of silicon low gain avalanche diode sensors are at various stages of production with varying fabrication parameters. Figure 1 shows a rough schematic of the masks used; each wafer includes sensors with active areas between 3 and 10 square millimeters.

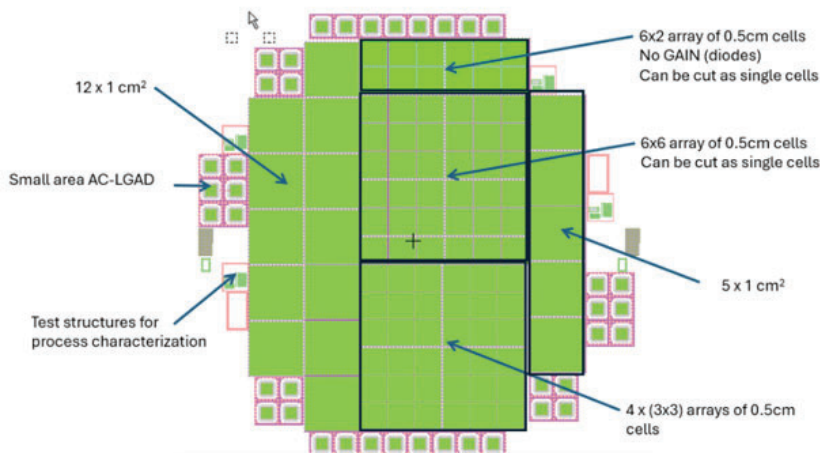


Figure 1: Rough schematic of masks used for wafer fabrication.

Each wafer has a set of test structures, as well as diodes and low gain avalanche diodes of different sizes. Pairs of wafers are being fabricated with different implantation energies and epitaxial thicknesses.

The first sets of wafers, including pre-diced prototypes, are now ready to be tested. Testing will include current vs voltage and capacitance vs voltage characterizations to be done using a combination of Syracuse's facilities and the Everbeing probe station at Cornell. After characterization, wafers will be diced using the DISCO dicing saw before being mounted to printed circuit boards and wirebonded. Wirebonding will be done primarily with Syracuse's Hesse bonder, with the Westbond 7400A Ultrasonic Wire Bonder to be used should complications arise. Once the low gain avalanche diode samples are mounted and bonded, the devices will be tested using transient current technique to study the differences in signal formation and to determine spatial and timing resolutions.

Conclusions and Future Steps:

Low gain avalanche diodes are promising sensors to be used in upcoming particle collider experiments, but more testing is needed to determine the precise fabrication parameters to best optimize to specific designs. Prototype wafers will be tested for electrical characteristics using a variety of probe stations before being diced using the DISCO Dicing Saw and wire bonded to custom printed circuit boards. After dicing, the samples will undergo electrical tests before they are wire bonded to readout boards for further study. Comparisons between the low gain avalanche diodes and standard silicon diodes

will be made to further explore the capabilities and limitations of different solid-state detectors for particle physics applications.

References:

- [1] W. Krüger et al., "LGAD technology for HADES, accelerator and medical applications", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1039, 167046 (2022).
- [2] S. Dharani, "Particle Identification using Time of Flight in the International Large Detector ILD", Bachelorarbeit (Universität Leipzig, 2018), p. 41, <https://bib-pubdb1.desy.de/record/414330>.
- [3] S. V. Chekanov et al., "Physics potential of timing layers in future collider detectors", JINST 15, P09021 (2020), arXiv:2005.05221.
- [4] A. Apresyan et al., "Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam", JINST 15, P09038 (2020), arXiv:2006.01999.

Fabrication of Tantalum Based Superconducting Qubits at CNF

CNF Project Number: 3237-24

Principal Investigator(s): Valla Fatemi

User(s): Maciej Olszewski, Simon Reinhardt, Lingda Kong, Shilling Du

Affiliation(s): Cornell Applied and Engineering Physics (AEP)

Primary Source(s) of Research Funding: Nordtech (SQFAB)

Contact: vf82@cornell.edu, sfr64@cornell.edu

Research Group Website: <https://fatemilab.aep.cornell.edu/>

Primary CNF Tools Used: GCA 6300 DSW 5X g-line Wafer Stepper, Heidelberg DWL2000, Oxford 81 Etcher, Oxford 82 Etcher, PT770 Etcher - Left Side, JEOL 6300, Angstrom-Quantum, Zeiss Ultra SEM, AJA-Q2, Dicing Saw - DISCO, P7 Profilometer

Abstract:

We demonstrate fabrication of quantum devices based on tantalum on silicon films. Coplanar waveguide resonators fabricated from tantalum on silicon films show best in class performance. We fabricate transmon qubits from Ta/Si films and find that device performance is at the state of the art for superconducting qubits.

Summary of Research:

Superconducting qubits based on tantalum (Ta) thin films have demonstrated the highest-performing microwave resonators and qubits. This makes Ta an attractive material for superconducting quantum computing applications [1]. So far, deposition of the cubic (BCC) phase of tantalum has relied on high substrate temperatures exceeding 400 °C. Changing the sputter gas from argon to krypton we have recently demonstrated growth of BCC tantalum on silicon at growth temperatures as low as 200 °C [2]. This low temperature film growth enables compatibility with process standards used in the back-end-of-line semiconductor fabrication. The films grown using krypton show larger grain size and enhanced residual resistivity ratio, compared to films grown with argon.

Coplanar waveguide (CPW) resonators are fabricated from the Ta/Si films on 100 mm wafers using photolithography and an optimized recipe for dry-etching and resist stripping. Resonators made from Ta/Si films grown at low temperatures show best-in-class performance with a low power quality factor of 4.1 million for resonators with 3 μm gap. These resonators show higher performance than resonators built using niobium seeded growth of tantalum as well as resonators built from Ta/Si films grown at high temperature of 600 °C (Fig. 1)

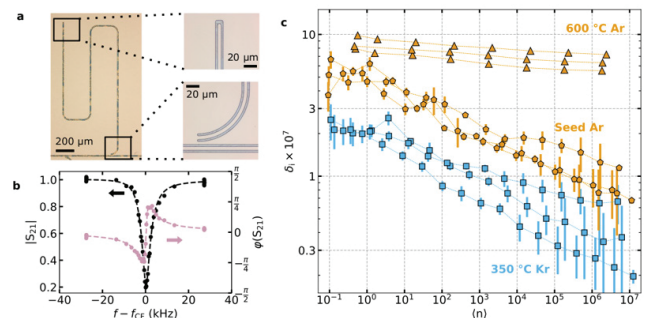


Figure 1: (a) Optical microscope image of a 100 nm thick Ta CPW resonator deposited with Kr at 350 °C. (b) Resonator quality factor measurement at single photon powers for 100 nm thick Ta CPW resonator deposited with Kr at 350 °C. Black indicates magnitude, while pink is the phase. (c) Power dependence of losses for three different types of resonators, from top to bottom: 600 °C Ar, RT Nb-seeded Ar, and 350 °C Kr.

We fabricate transmon qubits based on these high-performing Ta/Si baselayers. Josephson junctions of the Manhattan type are fabricated using shadow evaporation using MMA/PMMA masks. The masks are fabricated using electron beam lithography (JEOL 6300). For evaporation we use the newly installed Angstrom-Quantum tool, which provides in-situ Ar ion milling, thermal oxidation, and angled-evaporation of aluminum (Fig. 2, 3). Transmon devices are characterized in a dilution refrigerator at temperatures below 10 mK. We observe lifetimes and coherence times at the state of the art for superconducting qubits with T_1 times approaching 1ms and quality factors $Q_1 = 2\pi T_1$ fqubit clearly exceeding 10 million (Fig. 4).

Acknowledgements:

Funding (or Partial funding) for shared facilities used in this prototype was provided by the Microelectronics Commons Program, a DoW initiative, under award number N00164-23-9-G061.

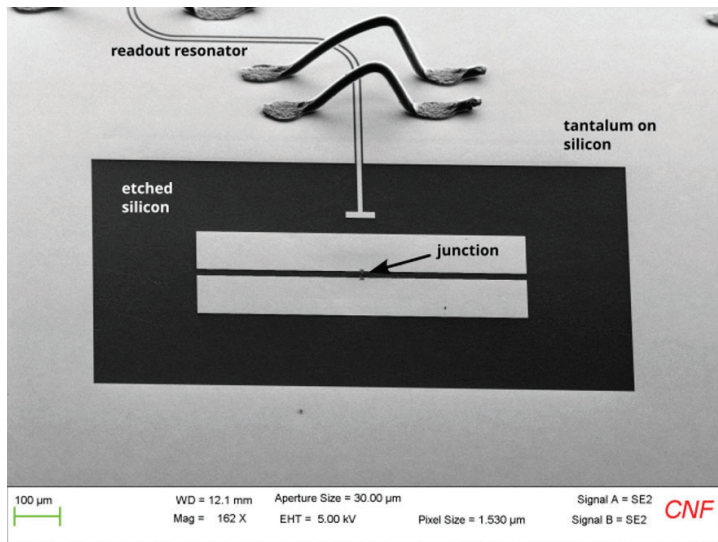


Figure 2: SEM of transmon qubit fabricated from Ta/Si film. The capacitor pads of size $120\ \mu\text{m} \times 800\ \mu\text{m}$ are separated by a $20\ \mu\text{m}$ gap. Wirebonds are used to remove spurious electromagnetic modes.

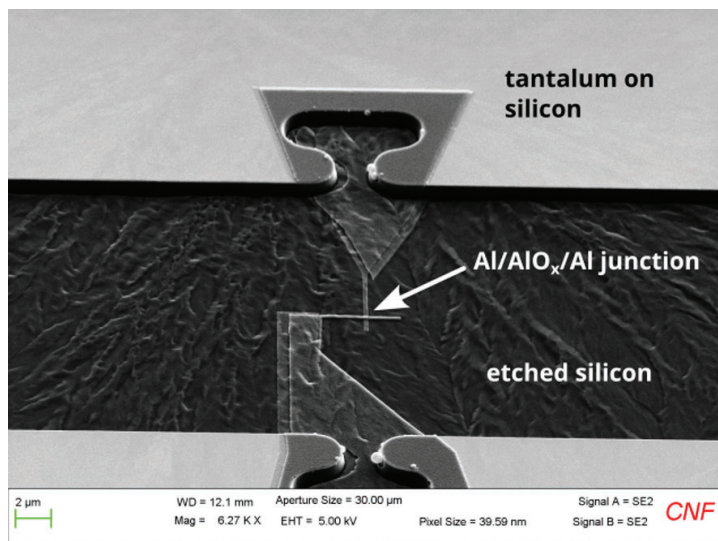


Figure 3: Zoom into Fig 2. shows the Manhattan-type Josephson junction. The Ta film is overetched by about $800\ \text{nm}$ into the silicon substrate. Etching the high-crystallinity Ta films results in high roughness of the etched silicon surface. Two electrodes are shadow-evaporated to form the Al/AIO_x/Al junction with an area of $\sim 200\ \text{nm} \times 200\ \text{nm}$.

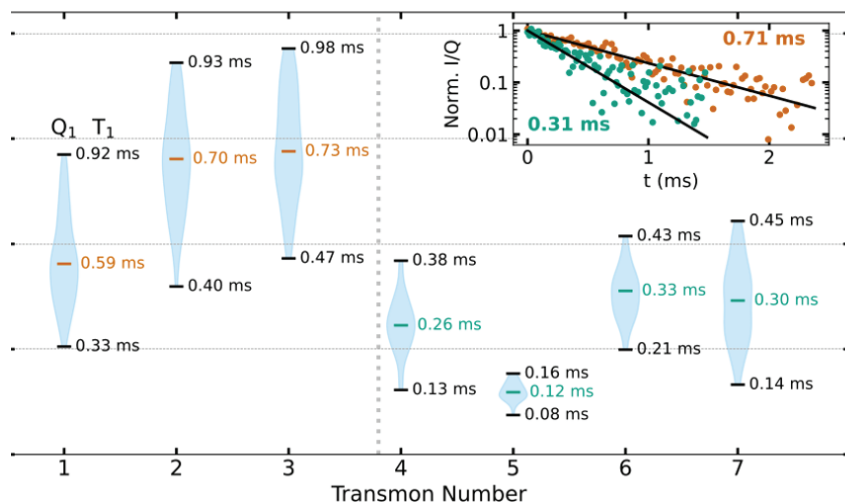


Figure 4: Violin plots of transmon quality factor for seven qubits measured; the distributions come from measuring T_1 repeatedly over about twelve hours. Values top to bottom represent maximum, median, and minimum lifetimes measured. Transmons 1-3 were fabricated without an oxygen descum, while transmons 4-7 had an additional oxygen descum. Insert has two example plots of lifetimes near the median value for both sets of devices.

References:

- [1] M. P. Bland et al., Millisecond lifetimes and coherence times in 2D transmon qubits, *Nature* 647, 343–348 (2025).
- [2] M. W. Olszewski et al., Krypton-sputtered tantalum films for scalable high-performance quantum devices, arXiv:2601.20091 (2026).

Study of Vortex Dynamics in Josephson Junction Arrays

CNF Project Number: 3265-25

Principal Investigator(s): Katja Nowack

User(s): Cequn Li

Affiliation(s): Laboratory of Atomic and Solid State Physics, Cornell University

Primary Source(s) of Research Funding: US Department of Defense

Contact: kcn34@cornell.edu, cl2775@cornell.edu

Research Group Website: <https://nowack.lassp.cornell.edu/>

Primary CNF Tools Used: JEOL JBX-6300FS, Heidelberg MLA 150 Maskless Aligner, Angstrom E-Beam Evaporator, AJA sputter, Zeiss Ultra SEM, Zeiss Supra SEM, Glen 1000 Resist Strip

Abstract:

An array of Josephson junctions provides a tunable platform for studying competing vortex states and the quantum phase transitions [1-4]. Here, we fabricate Nb-Au Josephson junction arrays and study vortex dynamics by combining electrical transport measurements and scanning superconducting quantum interference device (SQUID) microscopy. Our preliminary data shows the presence of periodic vortex lattice formed in the square and hexagonal arrays. Experiments on the vortex dynamics driven by an external current will be studied.

Summary of Research:

We fabricated Nb-Au Josephson junction arrays (JJA) and studied the formation of commensurate vortex patterns using transport measurements and scanning superconducting quantum interference device (SQUID) microscopy at low temperatures. Figure 1 illustrates the process to fabricate Nb-Au JJAs. First, we patterned Au/Ti (40/5 nm) films on Si substrates using optical lithography and electron-beam evaporations. Then we performed electron-beam lithography and sputtered Nb/Ti (70/2 nm) on the pre-patterned Au/Ti. Figure 2 shows an SEM image of an exemplary Nb-Au square JJA device. The Nb islands are only connected by the underneath Au films, forming superconductor-normal metal-superconductor networks.

The JJAs were characterized by low-temperature transport measurements. We confirmed the JJAs are superconducting with the critical temperatures ranging between 5 K and 7 K. Furthermore, we observed maxima in the critical currents as a function of the external magnetic fields, indicating the formation of periodic vortex lattices [2]. We also performed scanning SQUID measurements to visualize the vortex lattices at

different magnetic fields.

Conclusions and Future Steps:

We successfully fabricated Nb-Au JJAs with the critical temperatures ranging between 5 K and 7 K. Through electrical transport measurements and scanning SQUID microscopy, we detected the presence of vortex lattice in the JJAs, leading to enhancements of the critical currents at specific magnetic fields. We will visualize the motion of vortices driven by an external current for the understanding of the vortex dynamics [3, 4].

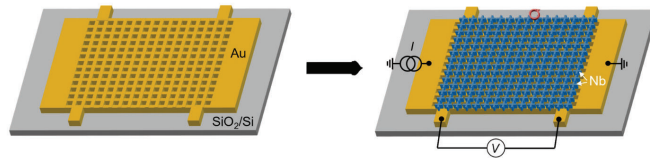


Figure 1: Schematics of fabrication process of Nb-Au Josephson junction arrays.

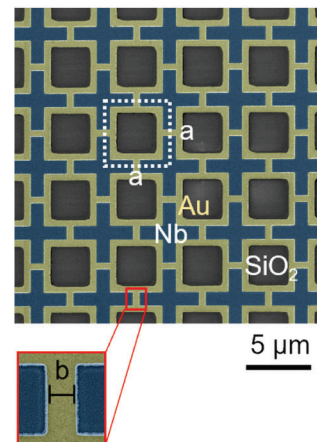


Figure 2: An SEM image of an exemplary Nb-Au JJA device.

References:

- [1] S. Teitel and C. Jayaprakash, Josephson-junction arrays in transverse magnetic fields, *Phys. Rev. Lett.* 51, 1999 (1983).
- [2] N. Poccia, T. I. Baturina, F. Coneri, et al., Critical behavior at a dynamic vortex insulator-to-metal transition, *Science* 349, 1202 (2015).
- [3] C. Böttcher, F. Nichele, M. Kjaergaard, et al., Superconducting, insulating and anomalous metallic regimes in a gated two-dimensional semiconductor–superconductor array. *Nat. Phys.* 14, 1138–1144 (2018).
- [4] C. Böttcher, F. Nichele, J. Shabani, et al., Dynamical vortex transitions in a gate-tunable two-dimensional Josephson junction array, *Phys. Rev. B* 108, 134517 (2023).

Thermal Transport Mediated by Non-equilibrium Surface Phonon Polaritons

CNF Project Number: 3280-25

Principal Investigator(s): Deyu Li

User(s): Xiaomeng Zhang and Xiaoyuan Huang

Affiliation(s): Department of Mechanical Engineering, Vanderbilt University

Primary Source(s) of Research Funding: National Science Foundation

Contact: deyu.li@vanderbilt.edu, Xiaomeng.zhang@vanderbilt.edu, Xiaoyuan.huang@vanderbilt.edu

Research Group Website: <https://lab.vanderbilt.edu/mntfl/>

Primary CNF Tools Used: AJA Ion Mill, AJA Sputter, GCA AS200 i-line Stepper, Glen 1000 Resist Strip, Heidelberg DWL2000, Keyence VHX-7100 Digital Microscope, Oxford 82 RIE, Oxford PECVD, PT VLN Deep Silicon Etch, Woollam RC2 Spectroscopic Ellipsometer, Xactix Xenon Difluoride

Abstract:

Surface phonon polaritons (SPhPs), quasi-particles resulting from coupling between infrared photons and optically active phonons, have attracted increasing attention as energy carriers for thermal radiation and heat conduction. Recently, we have observed that a short segment of Au-coating at the end of SiC nanowires could efficiently launch SPhPs to a number density that is orders of magnitude higher than the corresponding equilibrium values [1]. These thermally stimulated high number density SPhPs could lead to novel thermal transport phenomena beyond expectations within the conventional heat transfer paradigm established upon near-equilibrium thermal transport. In this project, we fabricate microdevices with integrated resistance heaters/thermometers to experimentally measure thermal radiation from individual nanostructures and heat conduction along individual nanowires mediated by thermally excited non-equilibrium SPhPs.

Summary of Research:

During the reporting project period, Dr. Xiaomeng Zhang has performed research at Cornell Nanofabrication Facilities two times to prepare microdevices for thermal measurements to examine SPhP-mediated heat conduction along and thermal radiation from individual SiC nanowires. She was able to successfully fabricate microdevices for both heat conduction (Figure 1) and thermal radiation (Figure 2). Based on these devices, we have successfully demonstrated an approach to measure thermal emissivity from individual nanostructures [2]. In addition, we have performed measurements to explore the effect of Au-coating morphology on SPhP-mediated thermal conductivity for individual SiC nanowires.

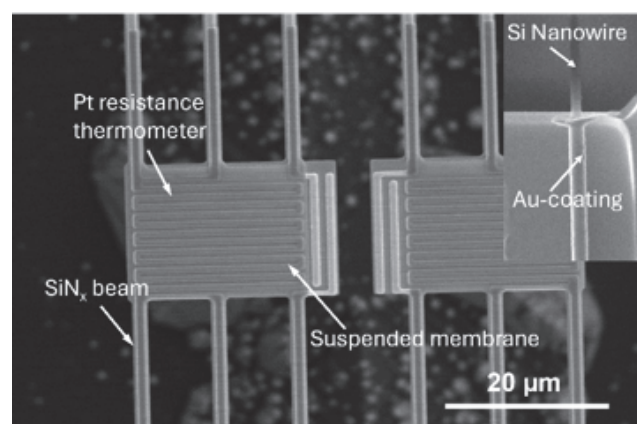


Figure 1: A scanning electron microscopy (SEM) micrograph of a microdevice fabricated at CNF for measurements of thermal transport through individual nanowires. Inset: An SEM micrograph of a SiC nanowire sample with Au-coating at the end placed on the microdevice.

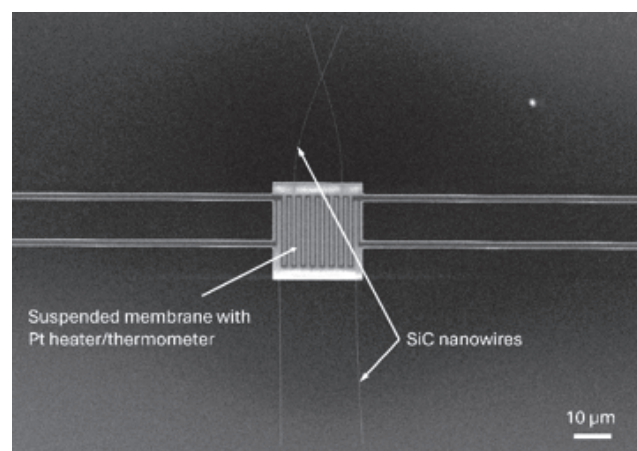


Figure 2: An SEM micrograph of a microdevice for measurement of thermal emission from individual nanowires. Individual nanowire samples have been placed on the device.

Conclusions and Future Steps:

The successful fabrication of microdevices at Cornell Nanofabrication facilities allowed for development of new thermometry techniques and currently we are conducting systematic studies to explore SPhP-mediated thermal transport. The results obtained could provide new insights into the physical properties of non-equilibrium SPhPs. We plan to design and fabricate devices with improved performance to further explore this emerging research topic.

References:

- [1] Z. Pan, G. Lu, X. Li, J. R. McBride, R. Juneja, M. Long, L. Lindsay, J. D. Caldwell, and D. Li, “Remarkable Heat Conduction Mediated by Non-Equilibrium Phonon Polaritons,” *Nature* 623, 307–312 (2023).
- [2] Z. Pan, X. Zhang, Z. Lai, M. Obst, J. D. Caldwell, and D. Li, “Differential Calorimetric Measurement of Thermal Emission from Individual Nanostructures,” *Rev. Sci. Instrum.* 96, 124902 (2025).

Surface Acoustic Wave Resonators for Measuring Superconductivity in 2D Materials

CNF Project Number: 3289-25

Principal Investigator(s): Brad Ramshaw

User(s): Nico Huber

Affiliation(s): Cornell University, LASSP

Primary Source(s) of Research Funding: Moore Foundation

Contact: bradramshaw@cornell.edu, nico.huber@cornell.edu

Research Group Website: <https://chill.lassp.cornell.edu/>

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, SC4500 Odd-Hour Evaporator, Zeiss Supra SEM

Abstract:

Surface acoustic wave devices can be used as a powerful probe for the electronic properties of 2D-materials [1,2]. Recently, surface acoustic wave resonators with high quality factors have emerged as an architecture with superior sensitivity over the traditional delay line geometry. By increasing the surface acoustic wave frequency, the quantum limit can be reached. In this regime the mean free path of conduction electrons exceeds the acoustic wavelength allowing for a k-space resolved measurement of the conductivity. In this project, we fabricated surface acoustic wave resonators on piezoelectric lithium niobate substrates and optimized the device geometry to increase their quality factor. We also pushed for smaller feature sizes to get closer to the quantum limit regime.

Summary of Research:

Resonators of different designs and fabrication parameters were fabricated using photolithography. To facilitate flexible and fast testing of different designs, the exposure was performed with a Heidelberg MLA150. The structures were then realized on the substrates using a Ti/Au deposition process through e-beam evaporation and subsequent lift-off. The resonators were characterized using a vector network analyzer. The best designs exhibited a quality factor of ~ 8000 , significantly improving on the designs previously used by our group (see Fig. 1). We additionally fabricated resonators that work at a resonance frequency of 1 GHz with feature sizes down to 1 micrometer.

Conclusions and Future Steps:

The improved design of the fabricated resonators allowed us to increase their sensitivity to the electronic properties of the materials we study with them. This enabled us to probe the transition between highly insulating and conducting states in graphene heterostructures and observe a superconducting transition in thin films of Nb.

In future work, we want to further improve the designs by using non-reflective transducers and will employ ebeam lithography to increase the resonance frequency up to several GHz in order to reach the quantum limit regime.

References:

- [1] Fang et al., PRL 130, 246201 (2023), Quantum Oscillations in Graphene Using Surface Acoustic Wave Resonators.
- [2] Song et al., PRL 136, 036301 (2026), Acoustoelectric Probing of Fractal Energy Spectra in Graphene/hBN Moire Superlattices.

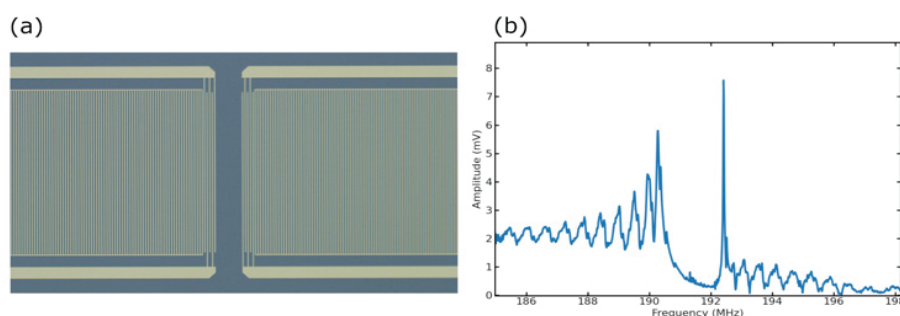


Figure 1: (a) Surface acoustic wave resonator on lithium niobate substrate. The resonator comprises a central cavity with interdigital transducers on either side that can be used for launching and sensing acoustic waves. Behind each transducer is an array of Bragg reflectors that confine the waves to the cavity. (b) Measured voltage at the sensing IDT as a function of frequency of a continuously applied RF voltage to the launcher IDT. The resonant mode at 192.5 MHz has a quality factor of ~ 8000 .

Resist-free Josephson Junction Fabrication for Superconducting Qubits

CNF Project Number: 3306-25

Principal Investigator(s): Valla Fatemi

User(s): Tathagata Banerjee

Affiliation(s): School of Applied and Engineering Physics, Cornell University

Primary Source(s) of Research Funding: National Science Foundation, Laboratory for Physical Sciences

Contact: vf82@cornell.edu, tb548@cornell.edu

Research Group Website: <https://fatemilab.aep.cornell.edu/>

Primary CNF Tools Used: JEOL 6300, Oxford 100, Oxford Cobra Silicon, Angstrom-Q, Heidelberg MLA150, Oxford 81, Primaxx vapor HF, Zeiss Ultra SEM

Abstract:

State-of-the-art Josephson junction fabrication depends on lift-off processes to define the superconductor-insulator-superconductor trilayer, which introduces organic contaminants and limits materials choices. In this project, we have developed a completely resist-free approach to the Josephson junction evaporation step, which eliminates the issues arising from the lift-off approach. We fabricated superconducting qubits using the design and have found performance better than other novel qubit designs and lower performance variation than comparable qubits in literature.

Summary of Research:

We fabricated novel resist-free Josephson junctions, which do not have any resist on the surface at the time of the evaporation [1]. We leverage the shadowing effect of the sidewalls of silicon trenches during e-beam evaporation. By changing the width of the trench, we control the presence or absence of an overlap of the films from either direction, creating a junction in the middle (Fig. 1).

We use these junctions to fabricate qubits in the CNF and conduct post-fabrication cleaning with oxygen descum and vapor HF to reduce surface residues (Fig. 2). We find that the qubit relaxation times (T_1) and pure dephasing times (T_2) scale as a function of the gap between the capacitor pads of the qubit (Fig. 3). The best performing qubit has a performance better than any other proposed novel qubit design.

We also characterize the qubit over longer time periods to examine the fluctuations of the parameters (Fig. 4). We find that the best qubit shows a relatively gaussian distribution of coherence time over 36 hours, which is indicative of high stability. Allan deviation analysis shows deviations lower than any comparable qubit in

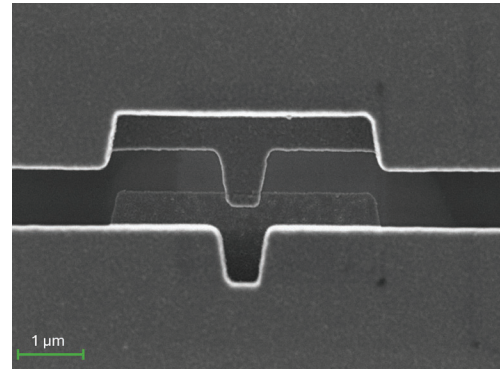


Figure 1: Top-down SEM image of the trench-based Josephson junction. No resist was used at the time of the junction evaporation, and thus there is no lift-off step necessary. Adapted from [1].

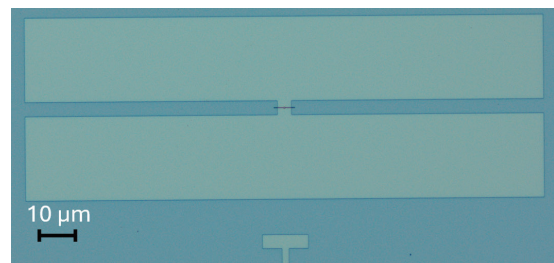


Figure 2: Fabricated qubit. The trench junction is in the middle, with rectangular capacitor pads to define the qubit capacitance. The qubit is coupled to a readout resonator to measure and characterize the qubit.

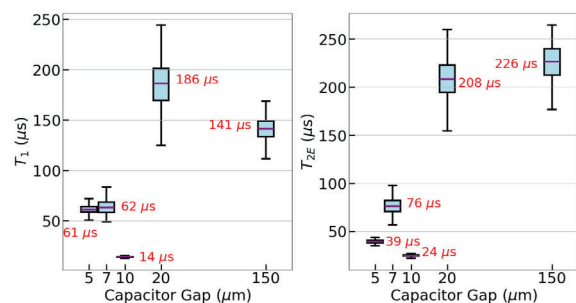


Figure 3: Qubit performance measurement. We measure qubit relaxation time T_1 and pure dephasing time T_2 over different capacitor gap distances and report. The performance increases as gap size increases. Data is reported in [1].

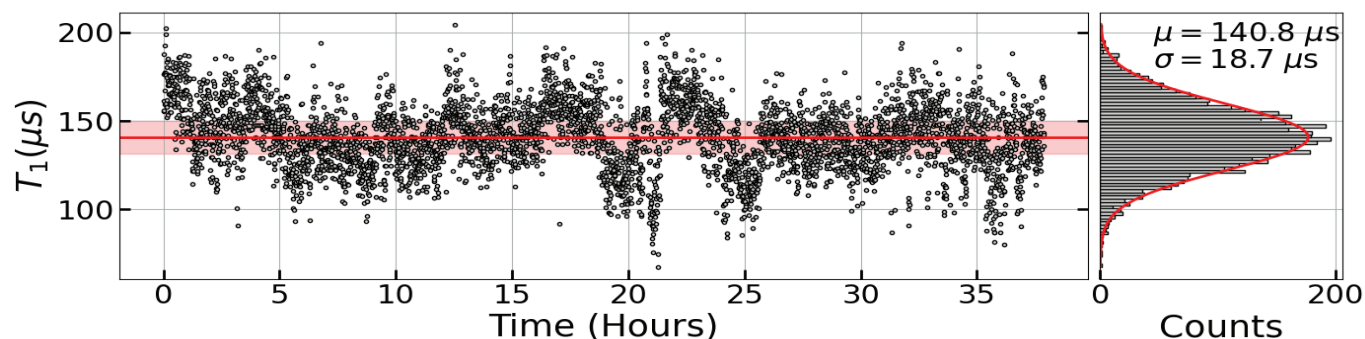


Figure 4: Coherence time fluctuations over 36 hours for one qubit, measured every 30s. We see a gaussian distribution, with standard deviation lower than equivalent qubits made with traditional fabrication processes. Adapted from [1].

the field, indicating that the elimination of the residues is likely causing a significant increase in the stability of the device.

Conclusions and Future Steps:

The ability to create such junctions creates several advantages, such as the elimination of organic residue between the junction and the substrate via aggressive HF cleaning, as well as the use of novel materials which can usually damage the resist if evaporated in the lift-off configuration.

The two primary insights from this work are the ability to try new materials and the reduction in qubit performance variation. Future work involves exploring further surface and interface preparation towards reducing the performance variation, and the use of materials such as Nb and Ta in conjunction with Al to leverage their properties to fabricate Josephson junctions.

References:

- [1] T. Banerjee, S.D. Funni, S. Roy, J.J. Cha, & V. Fatemi. Resist-free shadow deposition using silicon trenches for Josephson junctions in superconducting qubits, arXiv:2604.09796 (2026).

Fabrication of Silica Microtoroid

CNF Project Number: 3316-25

Principal Investigator(s): Xuefeng Jiang

User(s): Michael Kim

Affiliation(s): SUNY at Binghamton University

Primary Source(s) of Research Funding: Start Up Fund

Contact: xjiang11@binghamton.edu, mkim233@binghamton.edu

Primary CNF Tools Used: Electron-Beam Lithography (JEOL-9500X), SC4500 Odd-Hour/Even-Hour Evaporator, Yes Asher, Oxford PECVD, Oxford Cobra ICP Dielectric, Oxford 100 ICP Dielectric Etcher, PT770 Etcher – Left Side (Metal Etch), Disco Dicing Saw, Filmetrics F50, Microscope BX50

Abstract:

The primary objective of this research is fabricating a silicon nanostructured cavity device using Cornell NanoScale Science and Technology Facility (CNF) via high-precision micro- and nanofabrication processing. Building on preliminary work by the PI, post-fabrication characterization and performance metrics were evaluated at Binghamton University to determine the operational efficiency of the enhanced nanoscale design.

Summary of Research:

The fabrication process for the silicon nanostructured cavity device utilizes a bi-layer electron-beam lithography (EBL) process in combination with metal depositions to produce a metallic hard mask on the substrate. The overall objective is to establish a reliable and reproducible fabrication process capable of producing high-resolution nanoscale features for experimental characterization. Initial efforts concentrated on completing tool training, establishing process parameters, and optimizing each fabrication step to ensure process reliability before device fabrication.

The first stage of the project involved substrate preparation, cleaning, and resist processing. Since the available reference values for several fabrication tools required recalibration, the deposition and etch rates for silicon deposited by plasma-enhanced chemical vapor deposition (PECVD) and chromium were tested using pre-purchased wafer samples. Multiple calibration samples were fabricated and characterized to establish accurate process parameters. Film thicknesses were measured using the Filmetrics, allowing deposition and etch recipes to be refined before device fabrication commenced.

Once these procedures were completed, the silicon substrates were cut using the DISCO dicing saw to prepare individual samples for chromium deposition by electron-beam evaporation. Throughout the fabrication

process, several challenges related to contamination and reproducibility were encountered and addressed. Following the dicing procedure, microscopic black particulates were consistently observed on the substrate surface as shown in Figure 1.

To remove potential organic contamination, the samples underwent oxygen plasma cleaning using the YES Asher system. Additional troubleshooting was performed to identify the origin of the remaining surface particles. Several potential contamination sources were investigated, including debris generated during the dicing process, particulate contamination from nitrogen blow guns and squeeze bottles containing acetone or isopropyl alcohol (IPA). Each processing step was carefully evaluated to minimize contamination and improve overall sample cleanliness before lithographic processing.

Following substrate preparation, hydrogen silsesquioxane (HSQ) electron-beam resist was spin-coated onto the samples. The resulting resist thickness was measured using a KLA K7 profilometer through a scratch-test method to verify that the deposited film met the desired specifications. During the initial EBL exposure trials, unexpected substrate damage was observed after development as shown in Figure 2. Subsequent process analysis revealed that the damage originated from an unfavorable interaction between IPA and methyl isobutyl ketone (MIBK) used during the HSQ process. The HSQ was modified by using pure MIBK, eliminating the observed substrate damage and significantly improving process stability.

Chromium deposition by electron-beam evaporation was also carefully managed to preserve the integrity of the hard mask. Because chromium forms an oxide when exposed to air, deposition schedules were coordinated to minimize the time between evaporation and EBL exposure. Reducing air exposure helped maintain film quality and improved consistency throughout later

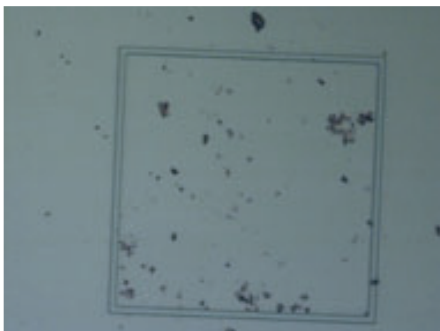


Figure 1: Snapshot of part of the cavity structure exposure with dirty particles appearing on the substrate

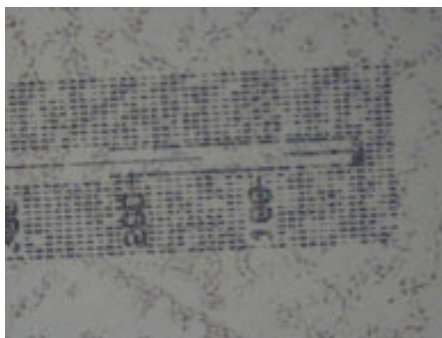


Figure 2: Snapshot of sample with the MIBK and IPA mixture with HSQ that is damaged

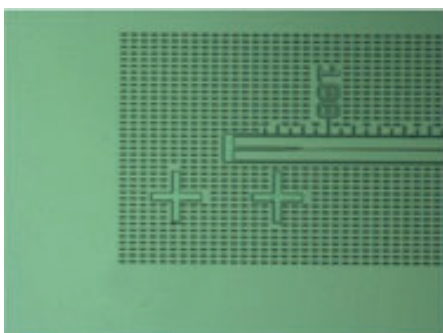


Figure 3: Snapshot of a part of cavity structure of the first layer from EBL, where there is minimal debris but appears there was some damage done in the middle of the structure. The exposure was completed using pure MIBK and HSQ.

processing stages. Following implementation of these process improvements, a satisfactory first-layer EBL exposure was successfully achieved with minimal surface contamination and well-defined lithographic features. Minor curvature of several pattern lines was observed near the center of the exposure field. This issue is believed to result from differences in beam calibration and exposure dose between the CNF electron-beam lithography system and the instrumentation previously used during process development. Rather than representing a fabrication failure, this exposure provided valuable information regarding dose sensitivity and beam alignment under the current process conditions.

Current work is focused on refining the EBL exposure parameters in collaboration with CNF technical staff to improve pattern exposure and accuracy. Additional efforts are directed toward optimizing process timing, minimizing contamination risks, and transitions between fabrication tools to increase overall process efficiency. These improvements are expected to enhance fabrication reproducibility and support the successful realization of the complete silicon nanostructured cavity device for subsequent experimental characterization at Binghamton University.

Conclusions and Future Steps:

For the next phase in our research, we focus on completing device fabrication for experimental evaluation at Binghamton University, with a targeted completion in early fall. Planned technical steps at CNF include calibrating the etch rates via ICP etching and scanning electron microscopy (SEM). Subsequently, the second electron-beam lithography (EBL) layer will be patterned, followed by e-beam silver deposition and a lift-off process. Any required process adjustments will be coordinated with CNF technical staff to ensure optimal device sample result before any process will begin.

Voltage-controlled Unconventional Magnon Spin Polarization for Logic-in-memory

CNF Project Number: 598-96

Principal Investigator(s): Daniel Ralph

User(s): Yuhang Liang

Affiliation(s): Laboratory for Atomic and Solid State Physics, Cornell University

Primary Source(s) of Research Funding: United States Department of Energy

Contact: dcr14@cornell.edu, yl3779@cornell.edu

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, AJA Ion Mill, C4500 Even-Hour Evaporator, AJA Sputter Deposition

Abstract:

Spin current provides an energy-efficient approach for manipulating magnetization, when its spin polarization aligns with the magnetization direction [1]. However, conventional spin-source materials possess high crystalline symmetry, restricting spin polarization to lie within the sample plane [2]. Here, we overcome this limitation by utilizing the concept of magnon-mediated spin-orbit torque through integration of a conventional spin-source material with the insulating multiferroic BiFeO_3 [3]. We observe that spin polarization generated by a conventional spin-source material can excite out-of-plane unconventional magnon polarization in BiFeO_3 . We further demonstrate a field-free spin-based logic-in-memory device controlled by ferroelectric polarization. Our results establish multiferroic-based heterostructures as symmetry-engineered magnon spin sources, paving the way for low-power spintronic devices.

Summary of Research:

By utilizing the collective excitation of magnetic materials, magnons [4], to carry the spin current, we experimentally demonstrate that the ferroelectric polarization in multiferroic BiFeO_3 enables control over magnon spin polarization in $\text{SrRuO}_3/\text{BiFeO}_3/\text{Ni}_{80}\text{Fe}_{20}$ heterostructures. Figure 1 shows a schematic of the device geometry and a micrograph of a completed spin-torque ferromagnetic resonance device used to detect the magnon spin polarization components. The SrRuO_3 layer is a high-symmetry spin-source material at room temperature, generating spin current polarization only along y-axis (within plane). The BiFeO_3 layer converts electron-mediated spin current from SrRuO_3 into magnon-mediated spin current. The $\text{Ni}_{80}\text{Fe}_{20}$ layer serves as detector to probe the orientation of magnon spin polarization in BiFeO_3 . To make electrical contact to the oxide and metal layers, we performed photolithography (Heidelberg MLA 150 Maskless

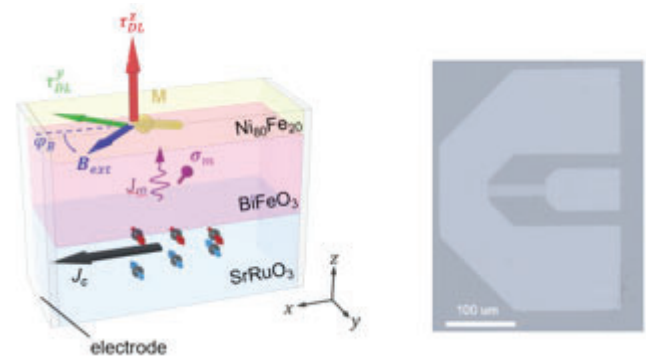


Figure 1: (left) Schematic for spin-torque ferromagnetic resonance measurement geometry and (right) optical image of fabricated device.

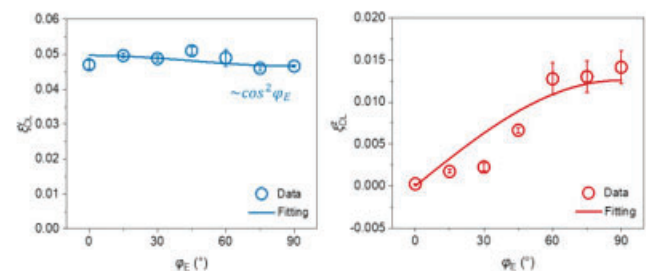


Figure 2: (left) Observation of conventional magnon spin polarization lies within sample plane and (right) out-of-plane unconventional magnon spin polarization.

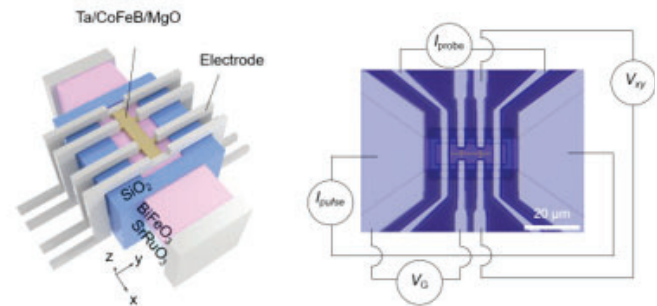


Figure 3: (left) Schematic of in-situ logic-in-memory device and (right) false-color optical image.

Aligner) and ion mill etching (AJA Ion Mill) to first expose micro-strips for microwave measurements. We then deposited Ti/Pt contacts with magnetron-sputtering deposition (AJA Sputter Deposition). We performed spin-torque ferromagnetic resonance measurements to characterize the orientation of magnon spin polarization. We observed efficient generation of conventional magnon spin polarization along y-axis, and out-of-plane unconventional magnon spin polarization along z-axis, with overall spin polarization rotated by up to 14° from the sample plane (Figure 2).

We then fabricated an *in-situ* device to control the out-of-plane unconventional magnon spin polarization via the ferroelectric polarization (see schematic in Figure 3). We deposited $\text{SrRuO}_3/\text{BiFeO}_3/\text{Ta}/\text{CoFeB}/\text{MgO}$ heterostructures, and then fabricated them into micro-strips (photolithography via Heidelberg MLA 150 Maskless Aligner and ion mill etching via AJA Ion Mill). We carefully etched the top CoFeB layer, ending at the BiFeO_3 surface (photolithography via Heidelberg MLA 150 Maskless Aligner and ion mill etching via AJA Ion Mill). We then deposited SiO_2 to isolate the top CoFeB channel and bottom SrRuO_3 channel (photolithography via Heidelberg MLA 150 Maskless Aligner and deposition via C4500 Even-Hour Evaporator). Finally, we deposited Ti/Pt contacts with magneto-sputtering deposition (AJA Sputter Deposition) (see optical image and measurement set-up in Figure 3).

In this *in-situ* device, a current pulse I_{pulse} applied along SrRuO_3 channel can switch the perpendicular magnetization of top CoFeB channel, and a gate voltage V_G can switch the ferroelectric polarization in BiFeO_3 . The CoFeB magnetization state is read out by small probe current $I_{\text{probe}} = 10 \mu\text{A}$ to probe the Hall resistance R_{xy} . By switching ferroelectric polarization through the gate voltage V_G , we successfully reversed the polarity of out-of-plane magnon spin polarization and demonstrated a spin-based logic-in-memory functionality at room temperature without any external magnetic field (Figure 4).

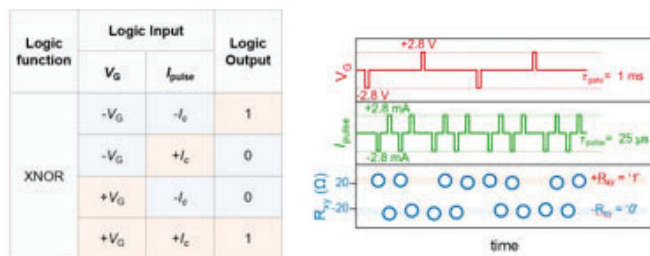


Figure 4: Truth table of spin-based XNOR gate (left) and experimental realization (right).

Conclusions and Future Steps:

In summary, we have shown that control of the ferroelectric polarization in multiferroic materials provides a route to control the magnon spin polarization, and we experimentally demonstrated an XNOR gate application. Our results may open pathways for advanced functionalities in future magnon-based spintronic devices.

References:

- [1] Manchon, A. et al. Rev. Mod. Phys. 91, 035004 (2019).
- [2] MacNeill, D., Stiehl, G., Guimaraes, M. et al. Nat. Phys. 13, 300–305 (2017).
- [3] Spaldin, N.A., Ramesh, R. Nat. Mater. 18, 203–212 (2019).
- [4] Chumak, A., Vasyuchka, V., Serga, A. et al. Nat. Phys. 11, 453–461 (2015).

Electrically Tunable Damping of Antiferromagnetic Nanowires

CNF Project Number: 598-96

Principal Investigator(s): Daniel Ralph

User(s): Matthew Roddy

Affiliation(s): Laboratory for Atomic and Solid State Physics, Cornell University

Primary Source(s) of Research Funding: U.S. Dept. of Energy through the CEEMag Center

Contact: dcr14@cornell.edu, msr285@cornell.edu

Research Group Website: ralphgroup.lasp.cornell.edu

Primary CNF Tools Used: GCA 5x g-line Stepper, Angstrom E-Beam Evaporator, Zeiss Supra SEM, Naby NPGS Nanometer Pattern Generator System, Oxford 81 RIE

Abstract:

In spintronics, antiferromagnets are an exciting option for many applications because of their advantages over ferromagnets, including ultrafast dynamics and resistance to stray fields. However, electrical detection and control of antiferromagnetic systems remain challenges. Through the assembly of vander Waals (vdW) materials, we fabricate three terminal heterostructures with a spin-source layer (TaIrTe_4), an antiferromagnet (CrSBr), and a tunnel contact (Graphite), which enables detection of the dynamics through the tunneling resistance. By etching these devices into a nanowire design, we show significant change in the linewidth of the antiferromagnetic resonant response, indicating strong control of the magnetic damping, through the applied current in the spin layer.

Summary of Research:

Spin torque nano-oscillators are magnetic devices that produce a high-frequency output in response to an applied direct current. Nano-oscillators have been realized in nanowire ferromagnetic systems where the intrinsic damping of a ferromagnet layer is offset by an applied spin current [1] and they produce signals at ferromagnetic resonance frequencies (typically in the GHz). An antiferromagnetic nano-oscillator would be highly desirable, as the higher frequency dynamics mean that the output would typically be in the high GHz to THz range that is more difficult to access. Recent results have shown that heterostructures of bilayer CrSBr , an A-type antiferromagnet, interfaced with a spin-source layer exhibits electrically tunable damping where the read-out of dynamics is achieved through changes in tunneling resistance [2].

In this project, we fabricate devices consisting of a TaIrTe_4 spin source layer, which has been shown to possess a large spin-Hall angle [3] interfaced with bilayer CrSBr to perform tunneling Spin-Torque Antiferromagnetic

Resonance (ST-AFMR) measurements. An example schematic of the device and measurement setup is shown in Figure 1.

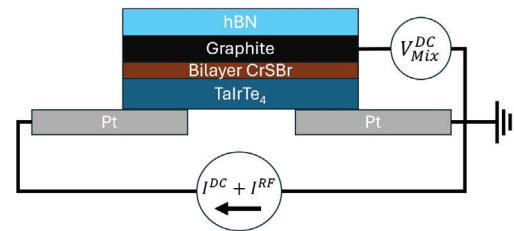


Figure 1: Device schematic showing the bilayer CrSBr tunnel junction with a TaIrTe_4 spin source layer with external sources setup to measure tunneling spin-torque antiferromagnetic resonances.

To begin, alignment grids are fabricated on high-resistivity silicon wafers using the GCA 5x g-line Stepper and the Angstrom e-Beam Evaporator to deposit a layer of Ti/Pd . Then the Zeiss Supra SEM and Naby Nanometer Pattern Generator System (NPGS) are used for e-beam lithography to pattern a set of three contact electrodes. These thin, Ti/Pt electrodes are deposited using the Angstrom e-Beam Evaporator once more to maintain sharp interfaces for the subsequent 2D material stack. Conventional vdW transfer techniques are used to stack and then place the materials on the contact electrodes in the following order: TaIrTe_4 ; bilayer CrSBr rotated approximately 45 degrees off the a-axis; graphite tunnel contact; and hBN to encapsulate the entire heterostructure and prevent air exposure during fabrication. A photograph of the device after stacking is shown in Figure 2a.

In order to fully tune the effective damping from positive to negative values and thereby achieve self-sustained oscillations it is necessary to minimize the device width, so these heterostructures are then etched into a nanowire. This is accomplished by using e-beam lithography with the Zeiss Supra SEM and NPGS to pattern the nanowire design (approximately 500 nm by 4 μm) and multiple

low-power plasma etches of different recipes using the Oxford 81 RIE to etch through each subsequent layer of the heterostructure. A photograph of the device after etching is complete is shown in Figure 2b.

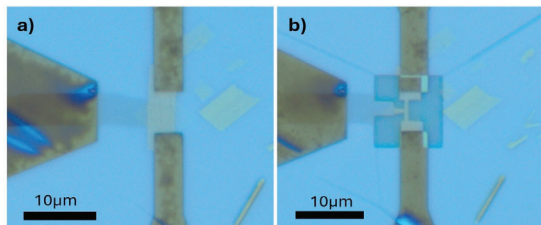


Figure 2: Photographs of the heterostructure a) after stacking and transfer of the vdW materials onto the contact electrodes b) after reactive ion etching into a nanowire.

ST-AFMR measurements are performed at a temperature of 30 K in a liquid He flow-cryostat. As depicted in Figure 1, a combination of RF and DC current is passed through the spin-source layer resulting in both a steady-state and oscillating spin-current incident upon the bilayer CrSBr. By sweeping the strength of a magnetic field along the intermediate axis of the CrSBr, the magnetization of each layer is tilted towards the field until the RF spin-current excites the optical mode response. This response results in an RF frequency change in the tunneling resistance, which mixes with RF leakage current through the tunnel junction to produce a measurable DC mixing voltage which can be detected through a lock-in amplifier. The steady-state DC current through the spin-source layer produces a constant damping or antidamping spin torque that will either enhance or counteract the intrinsic magnetic damping in the CrSBr, resulting in changes to the linewidth of the resonance shape. Example mixing voltage data as the magnetic field is swept are shown for multiple DC bias currents in Figure 3.

For small-angle precession, the resonances can be modeled as a summation of antisymmetric and symmetric Lorentzian line shapes. Fitting the resonances allows for the linewidth to be extracted, which is proportional to the damping of the antiferromagnet. Figure 4 shows the linear decrease in linewidth in response to increasing current, showing changes to the linewidth of 50% in either direction compared to the linewidth when no additional DC current applied.

Fig. 3: DC mixing voltage plotted against external field, at a frequency of 21 GHz, showing decreasing resonant linewidth in response to increasing DC bias current through the spin-source layer.

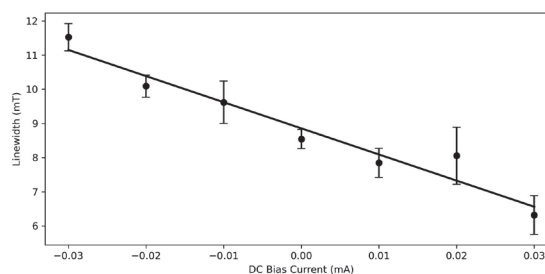
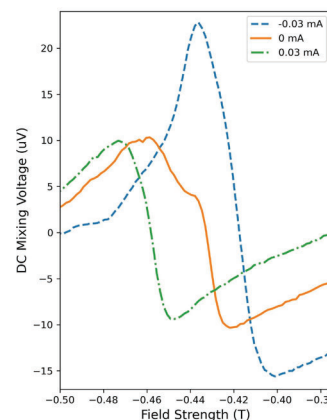


Figure 4: Linewidth extracted from the antiferromagnetic resonances at positive field, at a frequency of 21 GHz, as a function of applied DC-bias.

Conclusions and Future Steps:

We have shown a vdW heterostructure that exhibits significant changes to the ST-AFMR linewidth, and therefore the damping, in response to DC currents. Future experiments will seek to establish whether or not we can tune the damping in this system to negative values to create a nano-oscillator. While the excitations in this system are still in the GHz, this would be the first steps toward establishing antiferromagnetic oscillators for ranges of frequencies that are unachievable in conventional ferromagnetic oscillators.

References:

- [1] Smith, A. et. al. Phys. Rev. B 102, 054422 (2020).
- [2] Cham, T. M. J et al. Science 389, 479-482 (2025).
- [3] Bainsla, L., Zhao, B., Behera, N. et al. Nat. Commun. 15, 4649 (2024).

Anisotropic Conduction and Magnetoresistance in a Bilayer Antiferromagnetic Semiconductor

CNF Project Number: 598-96

Principal Investigator(s): Daniel Ralph

User(s): Bozo Vareskic

Affiliation(s): Laboratory for Atomic and Solid State Physics, Cornell University

Contact: dcr14@cornell.edu, bv227@cornell.edu

Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator System, Angstrom E-Beam Evaporator, Oxford 81 Etcher

Abstract:

We fabricate and characterize dual-gated transistors of bilayer chromium sulfur bromide (CrSBr). By fabricating samples where the current can be applied along different in-plane principal axes of the crystal, we characterize the anisotropic character of electronic transport by measuring the conductance as a function of top and bottom gate voltages. When current is driven along the a-axis, the transport reveals n-type semiconducting behavior with an electron mobility of $24 \text{ cm}^2/\text{Vs}$ and an on/off ratio of 10^3 . On the other hand, when current is applied along the b-axis, the on/off ratio is 10. We also characterize the magnetoresistance by applying a magnetic field in the out-of-plane direction. Our measurements reveal that the magnetoresistance is gate-tunable and can be as large as 600% when current is passed along the b-axis at $T = 20 \text{ K}$.

Summary of Research:

van der Waals magnets are promising candidates for next-generation spintronic devices [1]. A-type antiferromagnets display ferromagnetic correlations within the plane while adjacent layers couple antiferromagnetically. As a result, by applying an external magnetic field, the relative orientation of the magnetic moments of the layers can be tuned. Since, the nature and strength of interlayer electronic hybridization depends on the spin configuration, the electronic conduction properties of the antiferromagnet also vary with the orientation of the magnetic moments. CrSBr, is an A-type antiferromagnetic semiconductor with an ordering temperature of 130 K [2]. Here, we characterize the gate-dependent electronic conduction of bilayer CrSBr by performing transport measurements at $T = 20 \text{ K}$.

To fabricate our samples, we pattern and deposit thin Pt Hall bars onto a hexagonal boron nitride (hBN) dielectric layer that is interfaced with a few-layer graphite gate electrode from below. The Hall bar is patterned with

electron beam lithography using the Zeiss Supra SEM and Nabity Nanometer Pattern Generator System. The metal is deposited with the Angstrom E-Beam Evaporator. A top hBN and bilayer CrSBr are then transferred to the prepatterned Hall bar. Contact windows to the Pt Hall bar are then patterned and etched to expose the Pt layer. The etching is performed with a CHF_3/O_2 plasma using the Oxford 81 Reactive Ion Etcher. A final set of contacts to the exposed Pt are patterned and deposited using similar methods. A Ti/Au top gate and contacts to the bottom graphitic gate electrode are also deposited in the final deposition. Figure 1 shows a schematic of the device.

The top gate dependence of the conduction along the a-axis displays n-type semiconducting behavior as depicted in Figure 2. The conductance increases with increasing top gate voltage. In the linear regime, we can extract an electron mobility of $24 \text{ cm}^2/\text{Vs}$. The ratio of the conductance between the off and on state is 10^3 . Figure 3 gives the dependence of conduction along the b-axis with varying top gate voltage. In this case, the conductance is only tunable by one order of magnitude and the off-state conductance is two orders of magnitude higher than when current is passed along the a-axis.

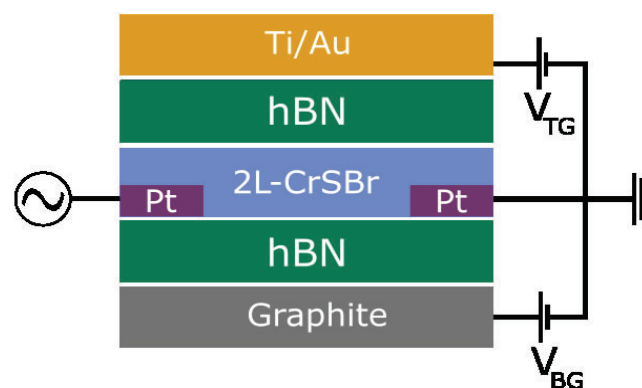


Figure 1: Device schematic of dual-gated bilayer CrSBr transistors. The bottom contacts are Pt, the top gate electrode is Ti/Au, and the bottom gate electrode is few-layer graphite. The CrSBr is encapsulated on both sides with dielectric hBN.

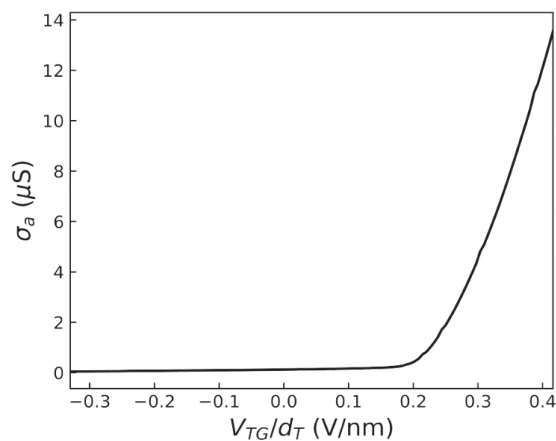


Figure 2: Four-point channel conductance as a function of top gate voltage with current passed along the a -axis. The top and bottom hBN thicknesses are given by d_T and d_B , respectively. The bottom gate is fixed at $V_{BG}/d_B = 0.3$ mV/nm.

We then measure the magnetoresistance of the bilayer by applying an external magnetic field in the out-of-plane direction. As the field increases, the moments of the two sublattices gradually cant towards one another until saturation. Figure 4 shows the magnetoresistance as a function of external field, B . The resistance is maximal at $B = 0$ and gradually decreases with increasing field until reaching a plateau at $B = 1.6$ T [3, 4]. The magnetoresistance is defined as:

$$MR(B) = (R(B) - R(B=3 \text{ T})) / (R(B=3 \text{ T})).$$

The magnitude of magnetoresistance increases with decreasing bottom gate voltage. We observe a maximum magnetoresistance of 600%.

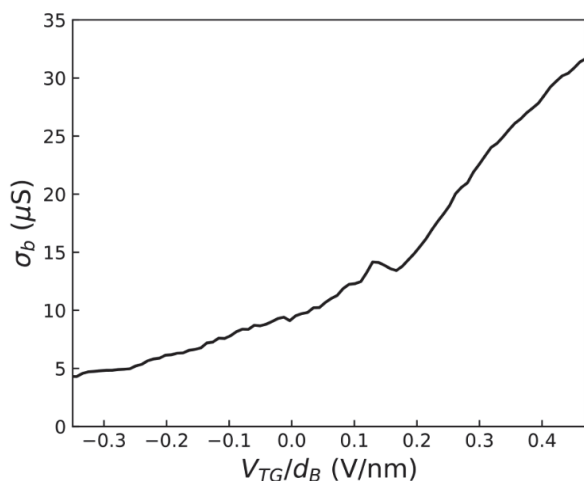


Figure 3: Four-point channel conductance as a function of top gate voltage with current passed along the b -axis. The bottom gate is fixed at $V_{BG}/d_B = 0$ V/nm.

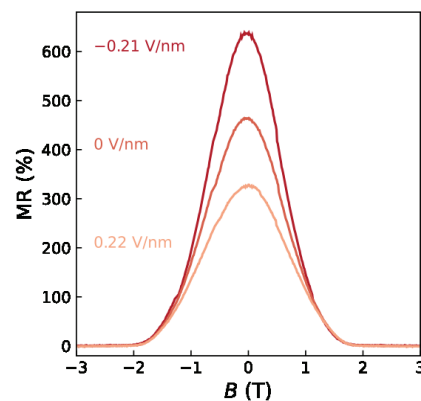


Figure 4: Magnetoresistance along b -axis as a function of out-of-plane magnetic field. The measurements are performed at constant top gate voltage of $V_{TG}/d_T = 0.47$ V/nm. The labels provide the values of V_{BG}/d_B .

Conclusions and Future Steps:

In summary, we have characterized the anisotropic conductance and magnetoresistance of bilayer CrSBr. Our measurements shed light on the relation between magnetic ordering and interlayer electronic hybridization.

References:

- [1] K. F. Mak, J. Shan, and D. C. Ralph, Nat. Rev. Phys. 1, 646 (2019).
- [2] M. E. Ziebel, M. L. Feuer, J. Cox, X. Zhu, C. R. Dean, and X. Roy, Nano Lett. 24, 4319 (2024).
- [3] E. J. Telford, A. H. Dismukes, R. L. Dudley, R. A. Wisconsin, K. Lee, D. G. Chica, M. E. Ziebel, M.-G. Han, J. Yu, S. Shabani, A. Scheie, K. Watanabe, T. Taniguchi, D. Xiao, Y. Zhu, A. N. Pasupathy, C. Nuckolls, X. Zhu, C. R. Dean, and X. Roy, Nat. Mat. 21, 754 (2022).
- [4] F. Wu, I. Gutiérrez-Lezama, S. A. López-Paz, M. Gibertini, K. Watanabe, T. Taniguchi, F. O. von Rohr, N. Ubrig, A. F. Morpurgo, Adv. Mat. 34, 2109759 (2022).

Characterizing Spin Wave Propagation in Lithium Aluminum Ferrite Thin Films

CNF Summer Student: Anabelle Brueggemann

Student Affiliation: Department of Physics, Lafayette College

Summer Program(s): 2026 Cornell NanoScale Facility Research Experience for Undergraduates (CNF REU) Program

Principal Investigator(s): Gregory Fuchs, Cornell University

Mentor(s): Yinshi Chen

Primary Source(s) of Research Funding: CEEMag EFRC

Contact: gdf9@cornell.edu, alb477@cornell.edu, yc2793@cornell.edu

Summer Program Website(s): <https://www.cnf.cornell.edu/education/reu/2026>

Research Group Website: <https://fuchs.research.engineering.cornell.edu/>

Primary CNF Tools Used: MLA150 Maskless Aligner, Oxford 81 Reactive Ion Etcher, AJA1 Sputter Tool, Sonicator, DSCO dicing saw

Abstract:

Lithium Aluminum Ferrite (LAFO) is a material that has emerged as interesting for applications in magnonics. Its low magnetic damping rate makes it ideal for magnon transport. The goal of this project is to investigate the nature of magnons propagating through LAFO. Scanning nitrogen-vacancy (NV) microscopy will be paired with coplanar waveguide readouts to image and quantify these spin waves. The first task is to fabricate a microchip stack that includes the LAFO thin film sample, coplanar waveguides to excite/readout spin waves, and a global microwave antenna to enable magnon detection. The LAFO is patterned using photolithography and ion milling, while the coplanar waveguides and the global antenna are fabricated using photolithography, metal deposition, and lift-off. The motivation for these experiments is the development of next generation, magnon-based interconnects for low-energy, intermediate scale data transfer.

Summary of Research:

As electronics scale down, copper interconnects have increasingly higher resistance, decreasing the efficiency of data transfer between devices. One mission of the “Center for Energy Efficient Magnonics” (CEEMag) is to investigate energy efficient interconnects in microelectronics that use spin waves, or magnons. Lithium Aluminum Ferrite, or $\text{Li}_{0.5}\text{Al}_{1.0}\text{Fe}_{1.5}\text{O}_4$ (LAFO), is the primary material we are investigating. It is a spinel ferrimagnet, and has an extraordinarily small Gilbert damping constant of about 0.004 [1]. This allows magnon propagation on an intermediate scale. We aim to characterize spin wave propagation in LAFO to explore its possible application in interconnects.

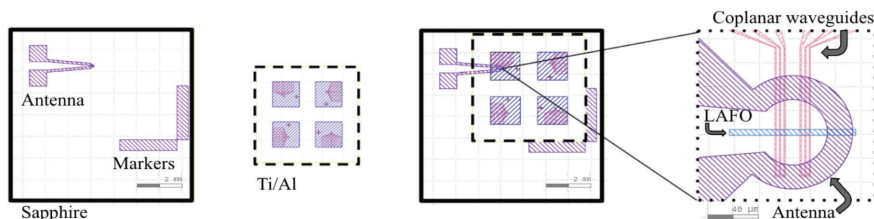


Figure 1: Chip Stack Design.

Our chip stack was fabricated in the Cornell Nanoscale Facility. The bottom layer of the chip, outlined in a solid line in Figure 1, hosts markers to place the top layer and a global antenna that will carry an RF signal. The top layer, outlined in a dashed line in Figure 1, has four identical sample sections, each with two coplanar waveguides, and a 100 by 1 micron sample of LAFO. The LAFO film, with a thickness of 35 nm, sits above the antenna, with a 500 micron offset. An RF current is sent through the first waveguide, exciting a magnon that propagates 20 micrometers along the LAFO sample to the second waveguide which gives a time-domain of the magnon’s amplitude. The underlying antenna emits an RF signal that interferes with the stray field produced by the magnon to aid in the scanning NV readout.

Scanning NV microscopy uses a point defect in diamond to detect micromagnetic properties of materials. This defect, the nitrogen-vacancy center, consists of a nitrogen substitutional atom with an adjacent carbon vacancy. Electrons in this center are sensitive to the surrounding magnetic field through their spin. In the scanning NV microscopy setup there is a diamond probe with an NV center at its tip, shown in Figure 2. The magnon produces an oscillating magnetic field with a constant spatial amplitude, but spatially varying phase. The NV center cannot detect this phase directly. Therefore, we need the global antenna to emit an RF signal which interferes with the stray field. This interference results

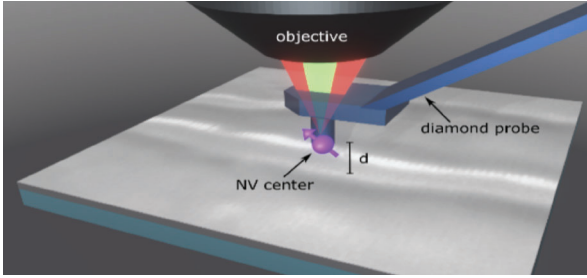


Figure 2: Scanning NV Probe.

in a static signal with a space-dependent amplitude. This signal is detected with the NV center to give a spatial image of the sample's micromagnetism. Pairing this with the electrical readout from the coplanar waveguide we can investigate how the magnon is propagating through the LAFO.

The fabrication of the bottom layer chip is done on a sapphire wafer. Layers of LOR3a and S1813 photoresist are deposited. The pattern is then exposed using the MLA150 maskless aligner and developed in AZ 726 MIF. Residual resist is removed with an oxygen plasma in the Oxford 81 reactive ion etcher. Next, the AJA1 is used to sputter on 10 nm of titanium and 150 nm of platinum. Finally, the lift-off of excess metal is facilitated by heating in 1165, and sonicating in 1165 and IPA. The devices are diced with the DSCO saw to fit into the printed circuit board, which can be placed in the scanning NV setup for measurements. The finished devices can be seen in Figure 3.

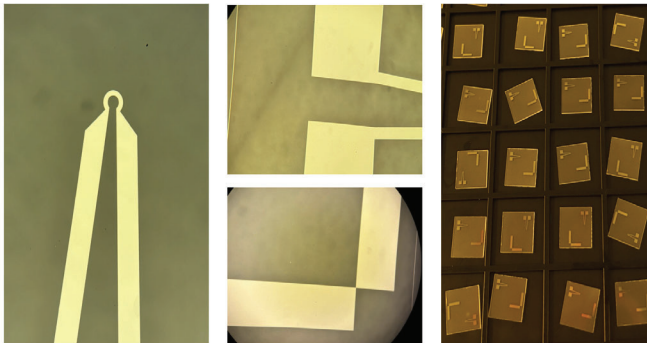


Figure 3: Fabrication Results.

In addition to this work, we have begun Mumax+ micromagnetic simulations to understand the physical meaning of future measurements. This aspect of the project is still developing, but the simulations show interesting effects.

Images in Figure 4 show samples of a different size than in our experiment to emphasize the pattern in the center of the sample, rather than the boundary effects. The bottom image in Figure 4 represents a continuous driving signal from the waveguide.

Boundary magnetic conditions, edge reflections, and coplanar waveguide geometry could be causing the variations seen along the edges of the sample. The upper images in this figure use a one nanosecond driving pulse. The top left image represents a pulse from the current coplanar waveguide geometry. The top right image represents a pulse from a waveguide without ground lines. The interference that appears around four nanoseconds in the left plot, but not in the right, suggests that these ground lines may be problematic. While there are more simulations to be done, these results may motivate the fabrication of new devices with altered coplanar waveguides.

Conclusions and Future Steps:

The current focus of this project is determining the parameters for scanning NV measurements. The RF signals and bias field needed for the experiment must be found before data is collected. Additionally, there is continuing work on mumax+ micromagnetic simulations.

After characterization of magnons in LAFO, the next step will be to test transmissions of spin waves at the boundary between LAFO and another material. This will build further understanding of how magnons behave at the interface between the propagation material and the material used for magnon detection.

Acknowledgements:

This work is supported by CEEMag at SLAC National Accelerator Laboratory, Cornell NanoScale Facility, Cornell University, and grant DE-AC02-76SF00515.

References:

- [1] O'Mahoney, Daisy, et al. "Aluminum Substitution in Low Damping Epitaxial Lithium Ferrite Films." *Applied Physics Letters*, 123(17), 172405 (2023). <https://doi.org/10.1063/5.0163362>.

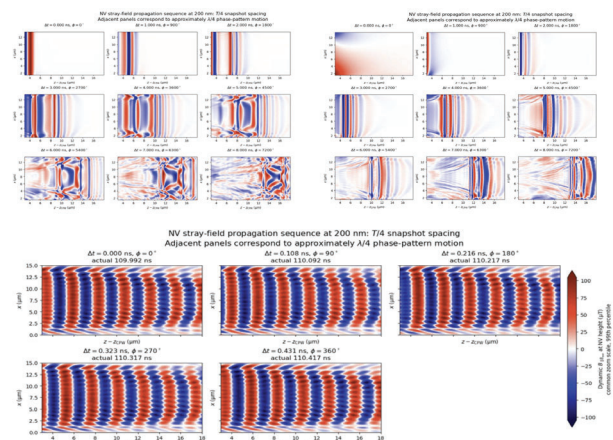


Figure 4: Preliminary Simulation Results.

ST-FMR Measurements of Low-symmetry Van der Waals Material TaIrTe₄

CNF Summer Student: Danaan Perry

Student Affiliation: Department of Physics, University of Illinois at Urbana-Champaign

Summer Program(s): 2026 Cornell NanoScale Facility Research Experience for Undergraduates (CNF REU) Program

Principal Investigator(s): Daniel Ralph, Cornell University

Mentor(s): Matthew Roddy

Primary Source(s) of Research Funding: CEEMag EFRC, U.S. Dept. of Energy

Contact: dcr14@cornell.edu, danaanp2@illinois.edu, msr285@cornell.edu

Summer Program Website(s): <https://www.cnf.cornell.edu/education/reu/2026>

Research Group Website: <https://ralphgroup.lassp.cornell.edu/>

Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, AJA Ion Mill, AJA Sputter Deposition, Veeco Icon AFM

Abstract:

Efficient magnetic memory requires compact storage through out-of-plane polarization as well as an energy-efficient write path. The write mechanism we are investigating uses out-of-plane spin-orbit torques (ZSOTs) to switch the magnetization of a thin ferromagnetic layer. These ZSOTs are not possible to generate in many materials due to symmetry restrictions; to overcome this, we study the low-symmetry van der Waals material TaIrTe₄. The current literature indicates that TaIrTe₄ produces strong ZSOTs, but measured values of the efficiency are inconsistent. The goal of this project is to fabricate test devices including TaIrTe₄ so that the efficiency of the ZSOT can be measured using the technique of spin-torque ferromagnetic resonance (ST-FMR).

Summary of Research:

Intro/Background

This project aims to contribute to the development of a write path for more energetically and spatially efficient magnetic memory. We can achieve this using the spin Hall effect. This effect occurs when running a conventional current through some spin source layer which generates a spin current that separates opposing spins on opposite surfaces of the spin source layer. This spin current can apply a torque onto the polarization of the ferromagnet, causing this magnetization to rotate. This effectively changes the state of the bit.

We are looking to examine the efficiency of TaIrTe₄ as a spin source. TaIrTe₄ is a low-symmetry van der Waals material. This low-symmetry property gives it the potential to produce out-of-plane torques (ZSOTs) that are most efficient for switching the state out-of-plane polarized magnets needed for improved high-density

memories. Current literature indicates that TaIrTe₄ not only produces ZSOTs, but that they are relatively strong. However, different measured values of TaIrTe₄'s spin Hall efficiency are inconsistent, motivating this initial exploration to validate the potential of TaIrTe₄ as a spin source.

Fabrication

Our fabrication process begins by exfoliating flakes of TaIrTe₄ onto a Si/SiO₂ substrate. Bulk crystals of TaIrTe₄ are adhered to scotch tape and pressed onto pieces of silicon wafer. TaIrTe₄ is air-sensitive, so we prepared samples in a glove box to prevent air exposure before transferring to the load lock of our sputter system where exfoliation was performed. The set-up for this procedure is shown in Figure 2a. This apparatus allowed for the tape to be peeled off in vacuum as samples were loaded into the main chamber. As a van der Waals material, small, thin flakes of TaIrTe₄ remain stuck to the silicon, providing uniform, single crystalline thicknesses. We then deposit 4 nm of Permalloy (Py) as our ferromagnetic layer and a 2 nm Ta capping layer to prevent air exposure. We then searched for thin, even, and at a minimum 5x5 μm flakes using an optical microscope (Figure 2c). Using the Veeco Icon AFM we confirm the actual thicknesses of chosen flakes and move forward with samples that were 40 nm or less.

We then used the Heidelberg MLA 150 to perform photolithography and the AJA Ion Mill to etch our Hall bars. When milling we incorporated breaks to avoid overheating the flakes or burning the resist. We again performed lithography to pattern the contacts. Before depositing our contacts using the AJA sputter system we do a 15 minute Ar plasma clean to remove any Ta oxide and create a better connection between our Hall bar and contacts. Finally we deposit about 60 nm of Ti/Pt to create the finished device shown in Figure 1.

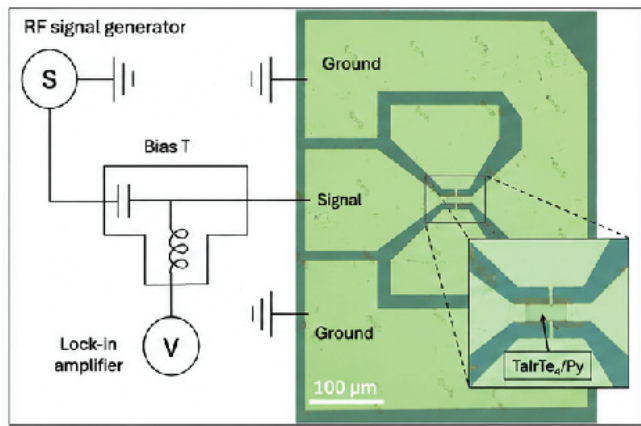


Figure 1: A completed device with GSG (ground-signal-ground) contacts for ST-FMR measurements. The enlarged area gives a closer look at the TaIrTe₄/Py stack. To the left is a diagram depicting the set-up used for ST-FMR measurements.

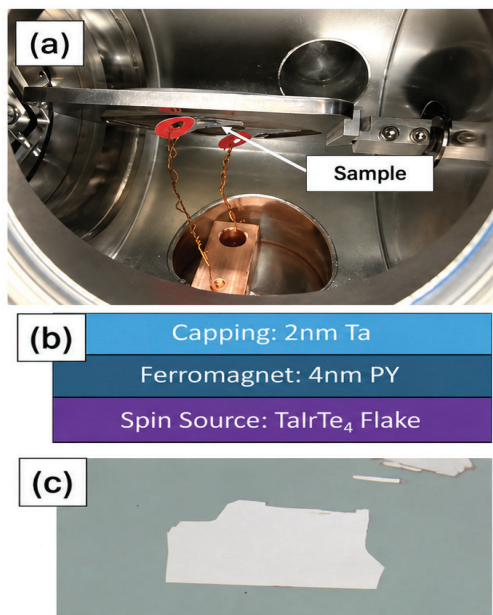


Figure 2: (a) Exfoliation apparatus in the load lock of the sputter system. (b) A complete stack consisting of a TaIrTe₄ flake 20–40 nm in thickness, 4 nm Py ferromagnetic layer, and 2 nm Ta capping layer. (c) Image taken on an optical microscope of a flake with dimensions of approximately 10 × 20 μm.

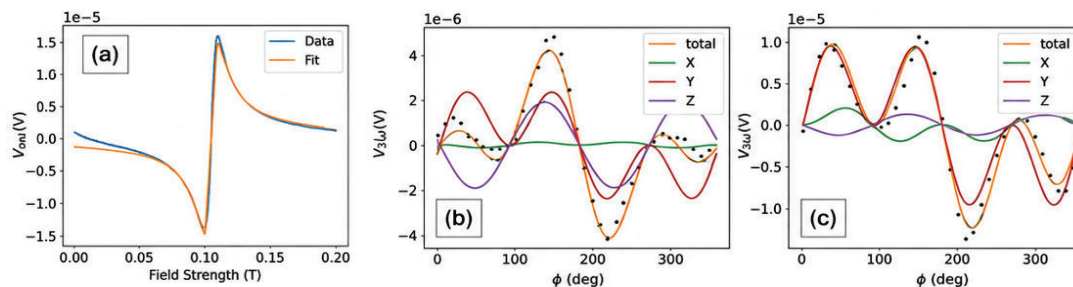


Figure 3: (a) V_{mix} vs. B_{ext} results at an applied angle of 30° degrees. In blue is the raw data and in orange the Lorentzian fit. (b) and (c) display the angular dependence for the symmetric (b) and antisymmetric (c) components of V_{mix} . The orange line is the total fit to the raw data in blue. The green, red, and purple lines then represent the X, Y, and Z components of the total as in Equation 1.

Results

We performed spin-torque ferromagnetic resonance (ST-FMR) measurements. ST-FMR works by measuring a changing voltage (V_{mix}) caused by anisotropic magnetoresistance of the ferromagnetic layer. V_{mix} can then be graphed against the external magnetic field (B_{ext}) and the resulting shape is a Lorentzian, pictured in Figure 4a, consisting of symmetric and antisymmetric components. These components can be separated, and their amplitudes graphed versus the angle at which the field was applied. The resulting angular dependences are shown in Figs. 4b and 4c and defined by the following functions.

$$S_{total} = S^y \cos(\phi) \sin(2\phi) + S^x \sin(\phi) \sin(2\phi) + S^z \sin(2\phi) \quad (1)$$

$$A_{total} = A^y \cos(\phi) \sin(2\phi) + A^x \sin(\phi) \sin(2\phi) + A^z \sin(2\phi) \quad (2)$$

The ZSOTs discussed are the Z-components in the above functions, with amplitudes SZ or AZ . We are primarily concerned with the symmetric component which we see has a significant contribution from the Z-component. These results therefore indicate that TaIrTe₄ does produce ZSOTs, the strength of which can be determined by further analysis.

Conclusions and Future Steps:

To conclude, we fabricated functioning TaIrTe₄/Py devices with TaIrTe₄ flakes ranging from 20–40 nm thickness for ST-FMR measurements. Our initial analysis determined that TaIrTe₄ does produce ZSOTs and with further measurements and analysis the strength of these torques will be determined. The next steps for this include Raman spectroscopy measurements to determine the crystal axis of the samples and determine the dependence of observed ZSOTs on crystal orientation. Then taking additional measurements, such as resistivity, to obtain all variables needed to formally calculate the spin Hall conductivity of our samples.