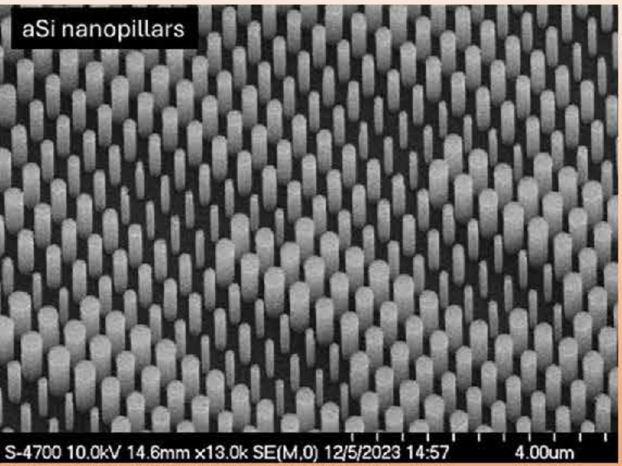
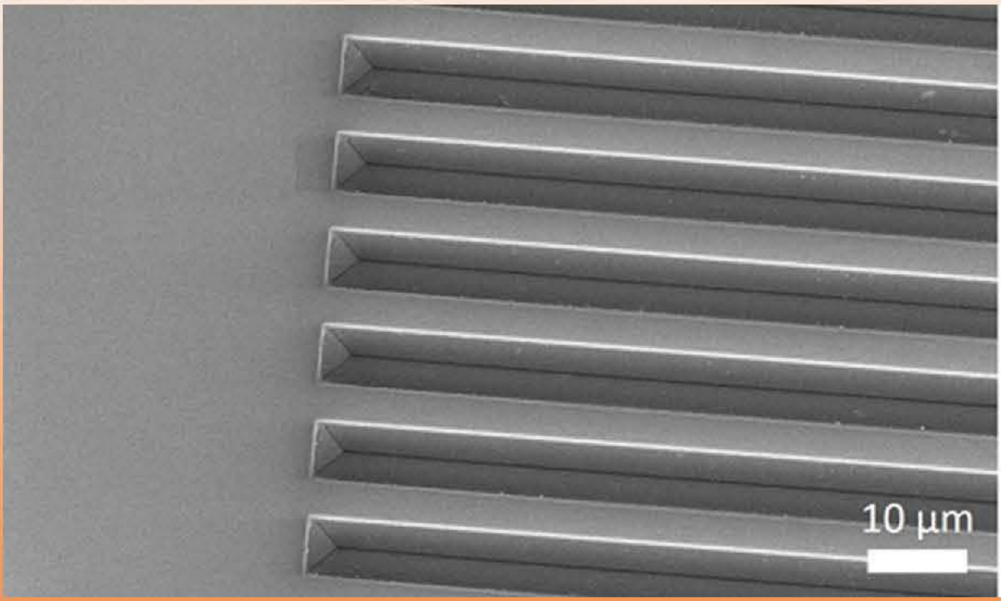
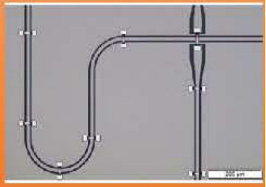
MNFC

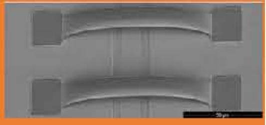
Micro/Nanofabrication Center

Research Report 2023









INTRODUCTION

The Micro/Nanofabrication Center (MNFC) at Princeton University, is 15,000-square foot cleanroom (ISO 5, 6 and 7 spaces) with a packaging and teaching laboratories. The MNFC cleanroom, and packaging lab has over 70 processing and metrology tools and serves users from both internal and external academics, as well as industry (see paragraph *MNFC USAGE STATISTICS* below). Also, in 2023, the MNFC supported ECE 308 Electronic and Photonic Devices course for undergraduate students (by Prof. Barry Rand) in 2,600 sqft cleanroom teaching laboratory.

The MNFC has capabilities in the areas of lithography (laser, contact, e-beam), wet processing, deposition (ALD, CVD, PVD), etching, 3D printing, and packaging (see paragraph *MNFC MAJOR EQUIPMENT*).

All MNFC labmembers are properly trained for working in a controlled environment during online, and in-person cleanroom orientation courses. Staff also performs one-on-one short courses to familiarize labmembers with how to prepare samples, and operate equipment. 84 new users have been trained, and qualified to work in MNFC in 2023.

2023 has brought several upgrades to our facility:

- The MNFC has extended Regular Hours from 9am-4pm (M-F) to 8:30am-5pm (M-F).
- We replaced the old, and faulty KLA P15 profilometer with a new P17 model.
- We installed a new bench-top sputterer for the quick coating of SEM samples.
- We provided a new Powersonic P230HTPC-132 ultrasonic cleaner with the frequency of 132kHz.
- The MNFC changed the hazardous waste collection system in three wet benches to minimize chemical exposure, and improve personnel safety. Cup sinks were replaced with safety funnels. Also, all wet benches in MNFC got equipped with aspirators.
- We upgraded the Chlorine gas cabinets, and installed Ultra-High Integrity Services Connections, DISS for connecting pigtails to the cylinders.
- The new tool freed time notification feature was created in NEMO.

This report outlines data collected through NEMO (MNFC software for managing access, reservations, tool, utilization, billing, etc.) about the MNFC, and research utilized in the facility between 1/1/23-12/31/23. The research reports were provided by researchers themselves. We thank all the MNFC labmembers who shared their data with us, and all your continued support.

CONTENTS

MNFC USAGE STATISTICS

Data presented below has been collected through NEMO, which is software for monitoring and controlling access to the facility, and to major tools within the facility. The Micro/Nanofabrication Center (MNFC) supported a diverse range of users and projects, as shown in Figure 1 below.

The MNFC served 179 labmembers in 2023, including researchers from 7 different Princeton University departments, 13 external academic users (including the University of Maryland, the University of Pennsylvania, and Rutgers University), and 22 industrial collaborators from 7 companies (see Figure 1). 86 MNFC labmembers were from PU Electrical and Computer Engineering department, and 19 of those researchers were members of prof. Nathalie de Leon's group.

The number of users in the MNFC has increased by 13% compared to the previous year, and by 47% compared to 2021.

Figure 1 A: Number of Princeton University Users vs. Research Group (2023)

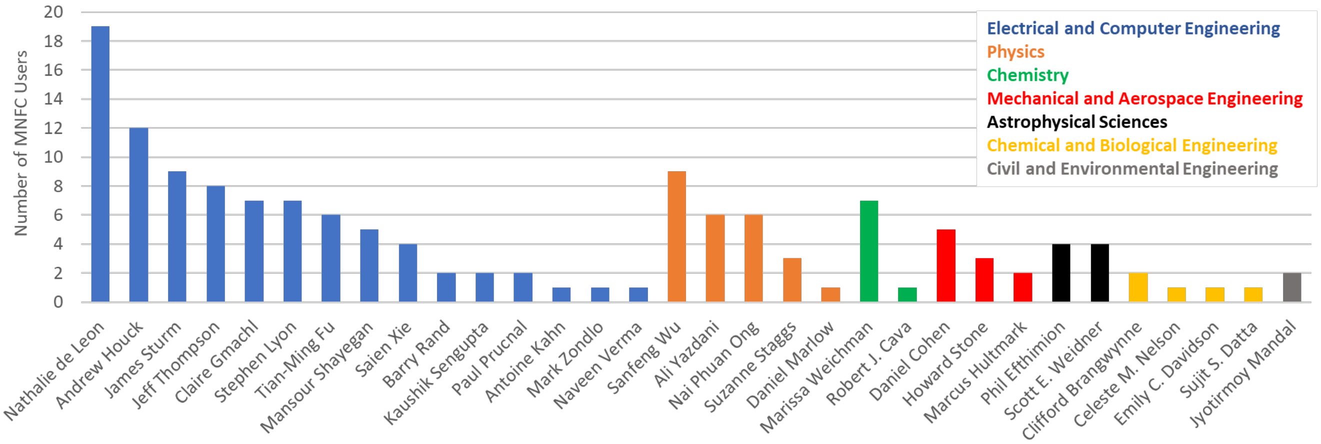
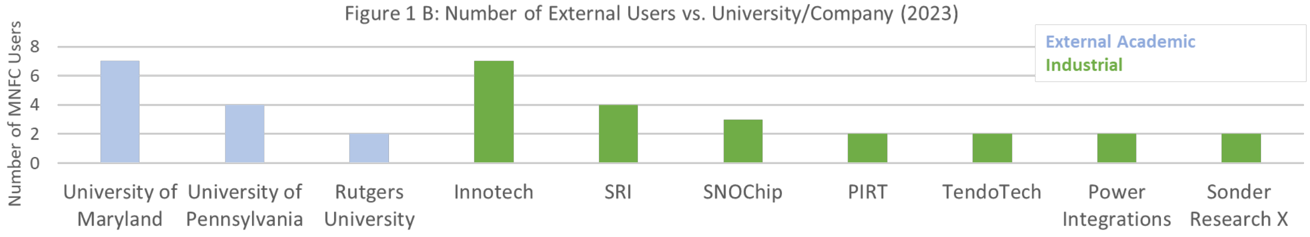


Figure 1 B: Number of External Users vs. University/Company (2023)



The Logins Count, which is the number of times the user has logged in to MNFC area (Cleanroom, SMP, Packaging) has increased by 34% compared to last year. 75% of the logins were to the Cleanroom Area (7099), 17% to Packaging (1633), and 8% to Soft Materials Laboratories (780).

In 2023, the facility was most busy during September and October. December is usually the quietest month at the MNFC (see Figure 2 below).

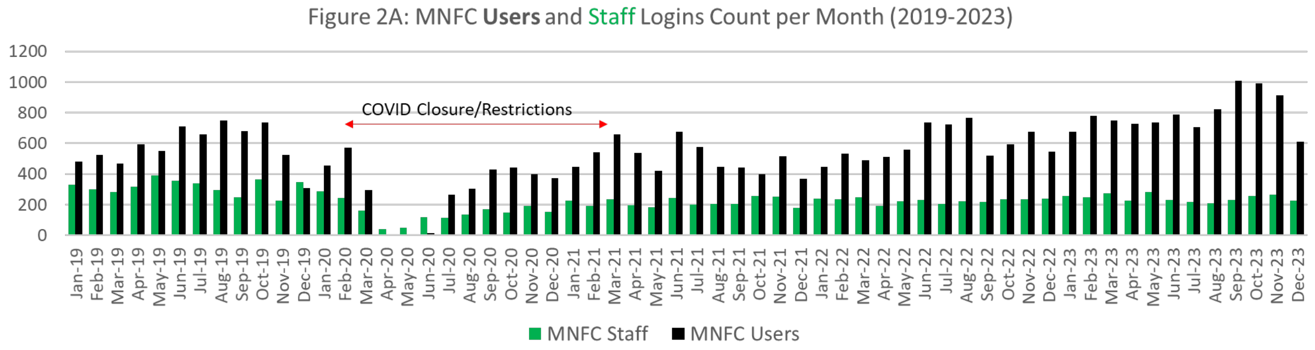


Figure 2A: MNFC **Users** and Staff Logins Count per Month (2019-2023)

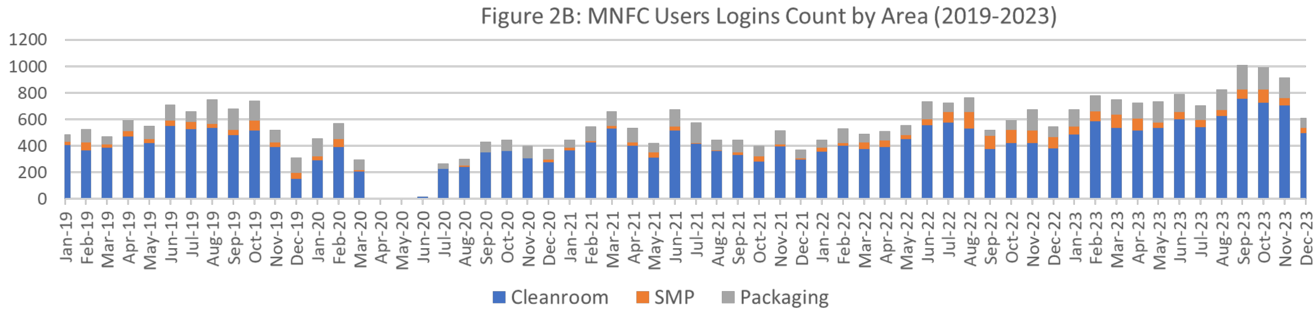


Figure 2B: MNFC Users Logins Count by Area (2019-2023)

The ratio of MNFC Staff to users in 2023 was 25. This ratio increased 150% compared to year 2019 (pre-pandemic time, see graph below). The right balance in staffing ratios is incredibly important for ensuring effective user support, and maintaining the overall health of MNFC operations. There were seven dedicated MNFC Staff members in 2023 (Zuzanna Lewicka, Joseph Palmer, Roman Akhmechet, Magdalena Moczala-Dusanowska, Brien Ely, Paul Cole, Bert Harrop), who had a mix of responsibilities. MNFC users were not involved in tool repair, maintenance, or training.

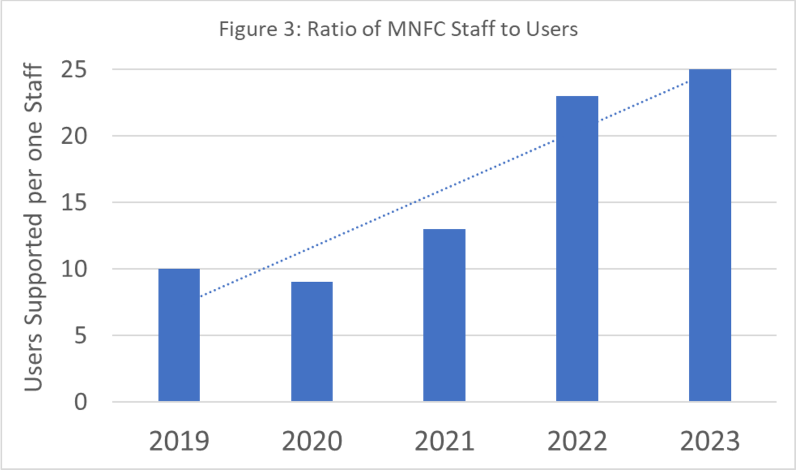


Figure 3: Ratio of MNFC Staff to Users

The two most used tools by labmembers in MNFC between January-December 2023 were the Raith EBPG e-beam lithography system (2028 hours, see Figure 4), and the Angstrom Covap thermal evaporator (1998 hours), the same as last year.

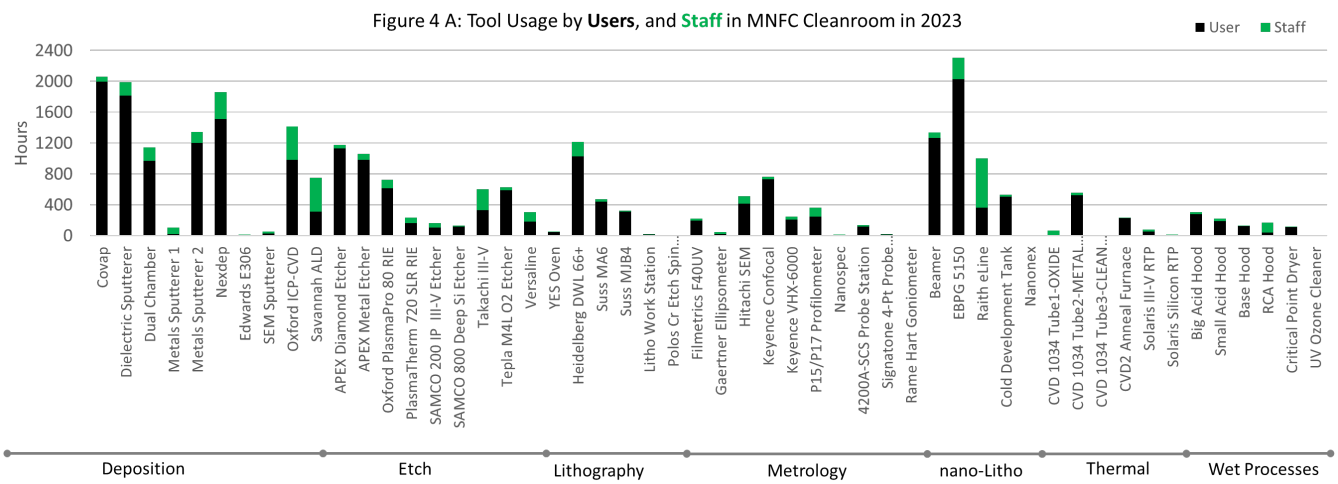


Figure 4 A: Tool Usage by **Users**, and **Staff** in MNFC Cleanroom in 2023

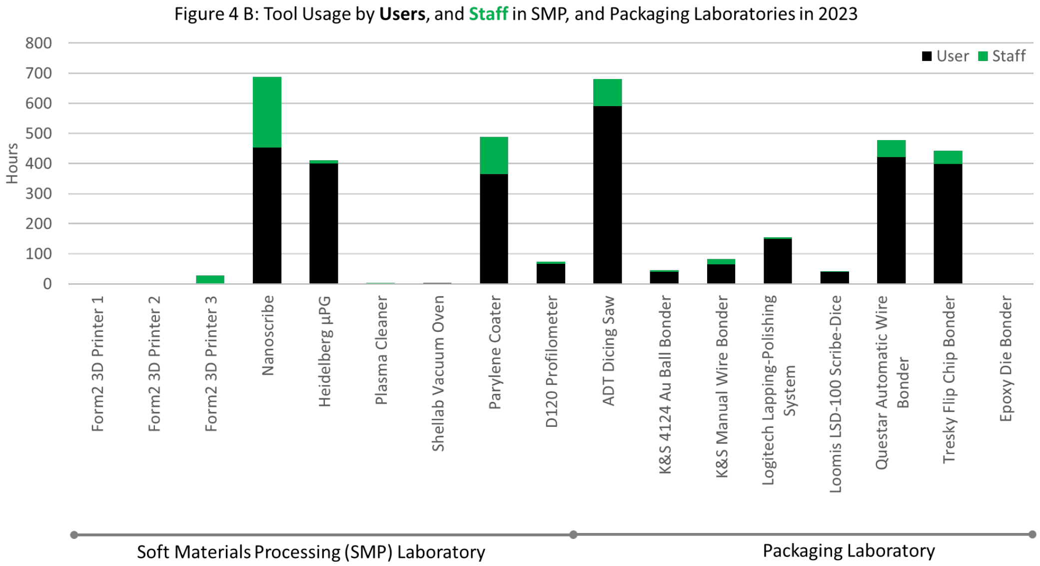


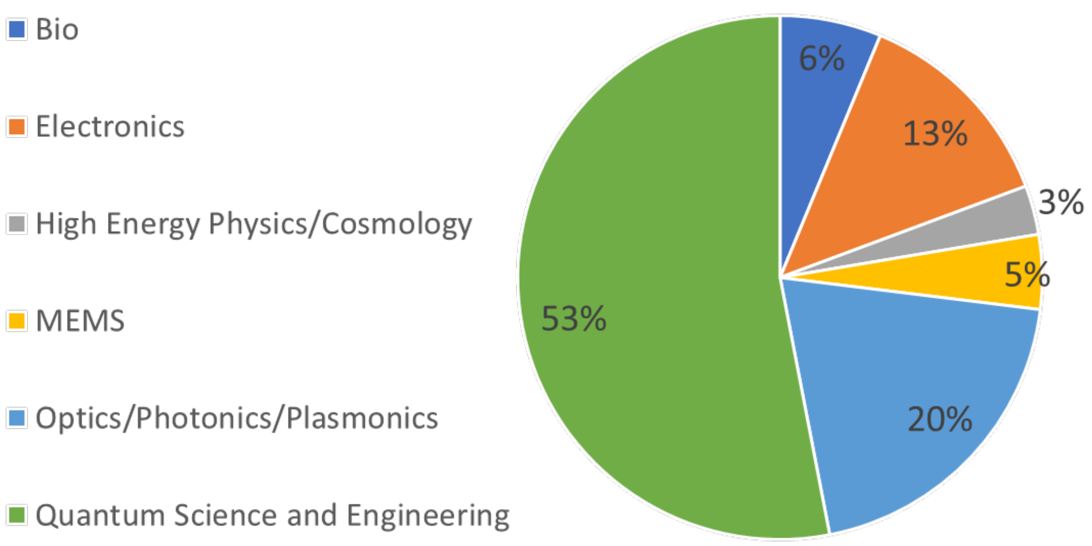
Figure 4 B: Tool Usage by **Users**, and **Staff** in SMP, and Packaging Laboratories in 2023

The MNFC facilitates multidisciplinary research for exploring new materials, creating novel devices and interfaces. Examples of last year projects are presented below in RESEARCH REPORTS section of this document (see also Figure 5), and include fabrication of:

- Platforms to study quantum effects (53%),
- Nano-photonics for the manipulation of light, lasers, detectors, and devices for detection and imaging (20%),
- Small electronic devices (13%),

- Implantable medical devices, microfluidic device, and printable materials for engineering cell behaviors (6%),
- Micro-electromechanical sensors (5%),
- Elements of devices to study fundamental particles and forces that constitute matter and radiation (3%).

Figure 5: Distribution of Tool Hours by Project Category.



MNFC MAJOR EQUIPMENT

DEPOSITION – PVD, ALD, ICP-CVD

- Angstrom metal sputter with a load lock
- Angstrom metal sputter with no load lock for fast and easy swapping of targets; with an argon ion gun for substrate pre-cleaning
- Angstrom dielectric sputter
- Angstrom dual chamber e-beam evaporator with six pockets, the upper chamber is a load lock for increased pumping speed
- Angstrom Nexdep single-chamber e-beam evaporator with six pockets
- Angstrom Covap thermal evaporator
- Edwards E306A thermal evaporator primarily for Indium evaporation
- SEM Sputterer
- Savannah ALD thermal Al_2O_3
- Oxford PlasmaPro 100 PECVD SiO_2, SiN_x, α-Si

LITHOGRAPHY

- Heidelberg DWL66+ with grayscale and backside alignment, 900 nm and 2 µm
- Suss MA6, MJB4 mask aligners
- Yield Engineering Systems oven for dehydration, HMDS priming, image reversal

NANO LITHOGRAPHY

- Raith EBPG 5150 high speed and high-resolution e-beam lithography writer, 100kV
- Raith E-Line e-beam writer, 5-30kV
- Nanonex Nanoimprinter

PLASMA ETCH

- PlasmaTherm Versaline Si precision etch: CF_4, CHF_3, C_4F_8, SF_6, O_2, Ar (is being installed)
- PlasmaTherm III-V etcher for vertical, smooth sidewalls: Cl_2, BCl_3, $SiCl_4$, CHF_3, SF_6, O_2, Ar, N_2 (is being installed)
- PlasmaTherm APEX SLR metal etcher: Cl_2, BCl_3, Ar, O_2, SF_6, and CHF_3
- PlasmaTherm APEX SLR diamond etcher: Cl_2, O_2, H_2, N_2, and Ar
- SAMCO 200iPB RIE (III-V and compound semiconductor); Cl_2, BCl_3, $SiCl_4$, Ar, and O_2
- SAMCO 800iPB Deep RIE (Si) using Bosch; SF_6, C_4F_8, O_2, CF_4, and Ar
- TePla isotropic asher; O_2, Ar, and CF_4
- PlasmaPro 80 RIE; SF_6, CF_4, CHF_3, O_2, Ar, and N_2 use: Si, SiO_2, SiN_x, SiC, Al, Al_2O_3
- PlasmaTherm 720 SLR RIE shallow etching of Si, SiO_2, SiN_x, some metals, and III/V's: Cl_2, BCl_3, H_2, Ar, O_2, SF_6, CF_4

THERMAL PROCESSES

- CVD Equipment atmospheric furnace system for oxidation and annealing
- SSI Solaris 150 Rapid Thermal Processing systems

SURFACE CHEMISTRY AND WET PROCESSING

- RCA processing hood
- Semi-Tool Spin Rinse Dryers
- Plasma surface activation
- UV / ozone cleaning
- Critical point dryer
- Automatic developer stations
- Polos chrome etch processor

METROLOGY

- Hitachi S-4700 SEM
- KLA Tencor P-17 profilometer
- Gaertner ellipsometer
- Filmetrics F40UV reflectometer
- Keyence confocal microscope
- Keyence VHX6000 digital microscope

SOFT MATERIALS PROCESSING

- Photonic Professional GT2 high resolution 3D printer
- Form Labs Form2 SLA 3D printers
- Heidelberg microPG101 (direct laser patterning of SU-8, 2µm and 5µm)
- PDMS processing tools: centrifugal mixer, degassing oven, curing oven, spin coater, punch press, plasma cleaner
- SCS Parylene coater
- KLA Tencor D-120 profilometer
- Probe Station, 4200A-SCS
- Signatone 4-Pt Probe Station
- Rame Hart goniometer

PACKAGING

- ADT Dicing Saw (taping, UV curing tools)
- Loomis LSD-100 Scribe/dice
- Wire Bonding: K&S Wedge, Questar Wedge, K&S Ball Bonder
- Logitech Lapping/Polishing System
- Tresky T-3000-FC3-HF Flip Chip Bonder
- West-Bond Manual Epoxy Die Bonder

RESEARCH REPORTS

Astrophysical Sciences

Advisor: Scott E. Weidner (Astrophysical Sciences)
Project Title: Improving and Understanding the Flight Components for the Solar Wind and Pickup Ion (SWAPI) Instrument Onboard the IMAP Mission
Researchers: John Teifert (Staff), Leng Ying Khoo (Postdoc), Tejaswita Sharma (Postdoc)

The IMAP mission is a NASA-funded mission that aims to understand the acceleration of energetic particles and the interaction of the solar wind with the interstellar medium [1]. Professor David McComas from the Department of Astrophysical Sciences is leading this mission that constitutes an international team of 24 partner institutions. The Princeton Space Physics Laboratory at 171 Broadmead is currently the home of the SWAPI instrument onboard the IMAP spacecraft. SWAPI is the first space instrument built by the Princeton Space Physics Laboratory and will provide simultaneous measurements of solar wind particles and pickup ions (PUIs), whose source is beyond our solar system, at 1 A.U. (the distance from the Earth to the Sun). See also Figure 1.

To make quality measurements in space, it is crucial to understand the characteristics of the flight components, in which we are fortunate to have the facilities like MNFC and the expertise there to understand and improve our flight parts. Our team has utilized microscopes like the Keyence Confocal microscope and Keyence VHX6000 to inspect and characterize the flight components such as the aperture grid shown in Figure 2. As indicated in Figure 1, the aperture grid is placed at the entrance of the instrument and will be used to attenuate the high-intensity solar wind by a factor of ~1000. The inspection performed at MNFC enables us to study the details of the aperture grid, and its result informs the selection of the final flight aperture grid as well as the modeling of the aperture grids.

In addition, our team has benefited from the PDMS processing tool to perform the Parylene coating on electronic boards. This step is crucial to ensure no leakage from the high voltage on the electronic boards and allow safe handling and testing of these boards. Because of the delicate nature of the components used in the construction of space instrumentation, handling is restricted to an extremely small number of qualified personnel. For similar reasons, components and assemblies are subject to an extremely strict chain of possession protocols. These requirements often require team members to travel with components in hand to vendors as needed. The capacity of the MNFC to support the SWAPI project provides tremendous savings in both travel expenses and personnel time.

For more details about the IMAP mission and the Princeton Space Physics Laboratory, please visit our website (https://spacephysics.princeton.edu) or our recent news highlight (https://discovery.princeton.edu/2022/12/12/soaking-up-the-sun/).

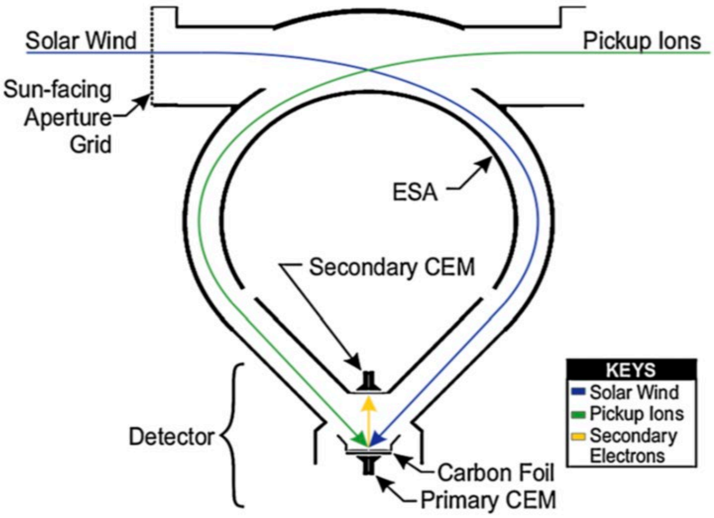
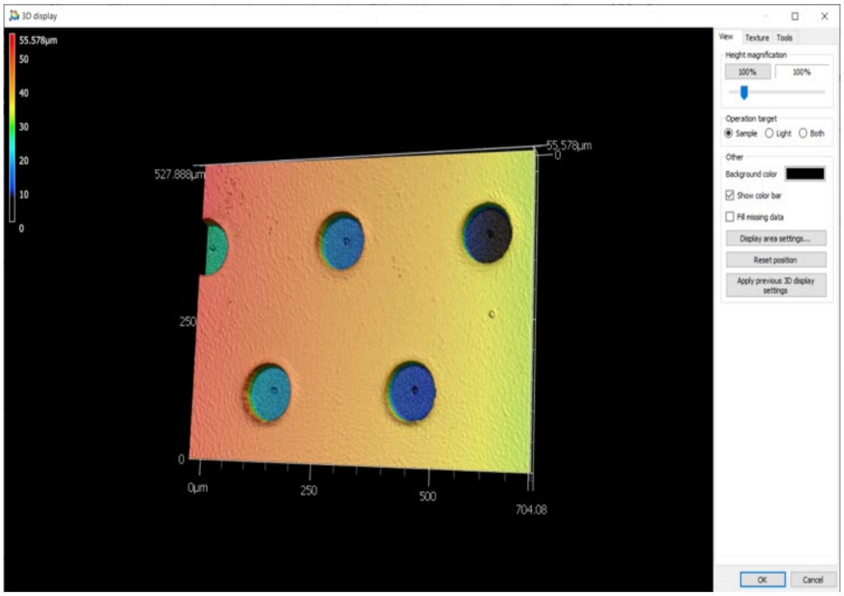


Figure 1: Cross-sectional view of the SWAPI sensor with blue trajectories that highlight the incident solar wind and green that highlight PUIs. Yellow trajectories show the path of the secondary electrons generated from the foil to provide the coincidence timing.


Height magnification 100% 100%

Operation target ● Sample ○ Light ○ Both

Other

☑ Show color bar

☐ Fill missing data

Figure 2: A closeup view of aperture grid in 3D, which consists of multiple small science openings (~10um) residing inside larger, non-through holes (~100 um). The grid is inspected using Keyence Confocal microscope available at MNFC. It informs us about the thickness of the non-through hole layer, and together with the overall thickness of the grid, we can infer the thickness of the science layer, which is one of the most important criteria for the final flight aperture grid.

CITATIONS:

McComas, D.J., Christian, E.R., Schwadron, N.A. et al. Interstellar Mapping and Acceleration Probe (IMAP): A New NASA Mission. Space Sci Rev 214, 116 (2018). https://doi.org/10.1007/s11214-018-0550-1

Advisor: Philip Efthimion

Project Title: Titanium Micro-Stripes for Radially Resolved X-ray Emission in Laser-Produced Plasmas

Researchers: Frances Kraus (Staff), Shawn McPoyle (Undergraduate), Kemal Atay (Undergraduate)
Sponsorship: Department of Energy, PPPL, LaserNetUS

Our research focuses on hot-dense plasmas that are created when high-intensity laser pulses are focused onto solid targets. Over the course of several picoseconds, the targets are heated, ionized, and ablated, producing ultrahot (2 keV or 20 million K) plasmas at solid density. We study this process with x-ray emission from the targets, but the large temperature and density gradients across the plasma make it challenging to interpret all x-rays emitted from all volumes in the target. Instead, we shoot targets with small amounts of tracer material deposited in limited areas, then only measure the x-rays emitted by this tracer material. In our recent LaserNetUS campaign at the Colorado State University ALEPH laser, we brought targets produced at the MNFC with titanium micro-stripes, which allow us for the first time to study radial gradients in the plasma. Micro-stripes are produced with lithography and physical vapor deposition, then overcoated so that they represent conditions inside the laser target. Analysis so far indicates that x-ray data from micro-stripe targets can yield temperature profiles as a function of radius across the plasma volume.

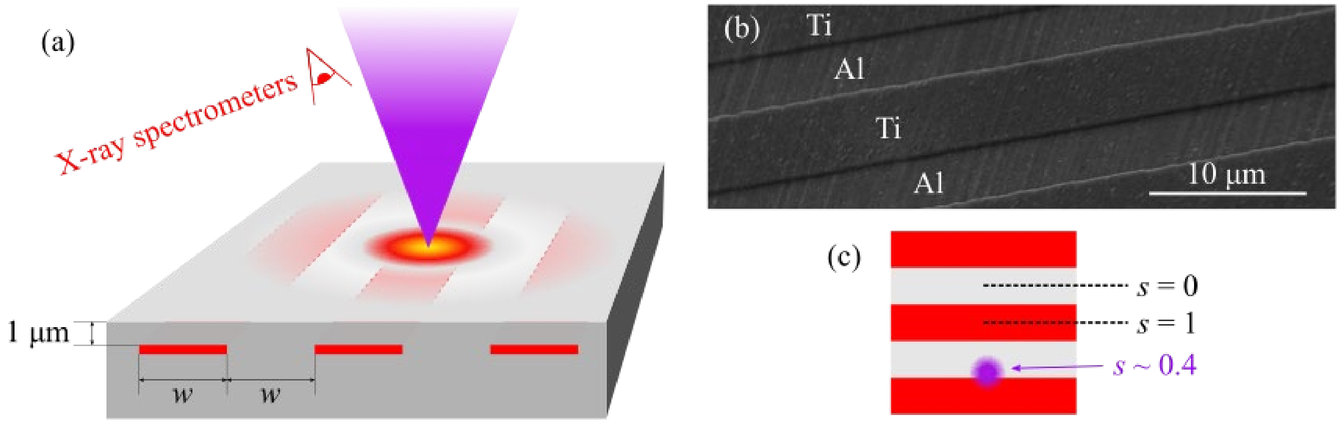


Figure: (a) A cartoon of a laser focusing on a micro-stripe target. The red represents Ti embedded inside an Al slab. (b) An SEM image of the Ti micro-stripes before they are overcoated with Al. (c) A schematic showing the range of possibilities for the laser to focus, where s=0 indicates a laser focusing between stripes, s=1 indicating a direct hit on the center of a stripe, and other values indicating off-center focusing. All values of s are useful for interpreting temperature profiles.

CITATIONS:

B. F. Kraus, S. P. McPoyle, K. Atay et al. “Electron temperature profiles in hot-dense plasmas from x-ray spectral ensembles.” To be submitted, Physics of Plasmas 2024

Chemical and Biological Engineering

Advisor: Cliff Brangwynne

Project Tittle: Mechanical Deformation During Cancer Cell Confined Migration Reshapes and Induces Nuclear Condensates

Researcher: Jessica Zhao (Graduate)

Sponsorship: HHMI

We investigate the impact of mechanical deformation on phase-separated assembly using a microfluidics-based confined migration assay.

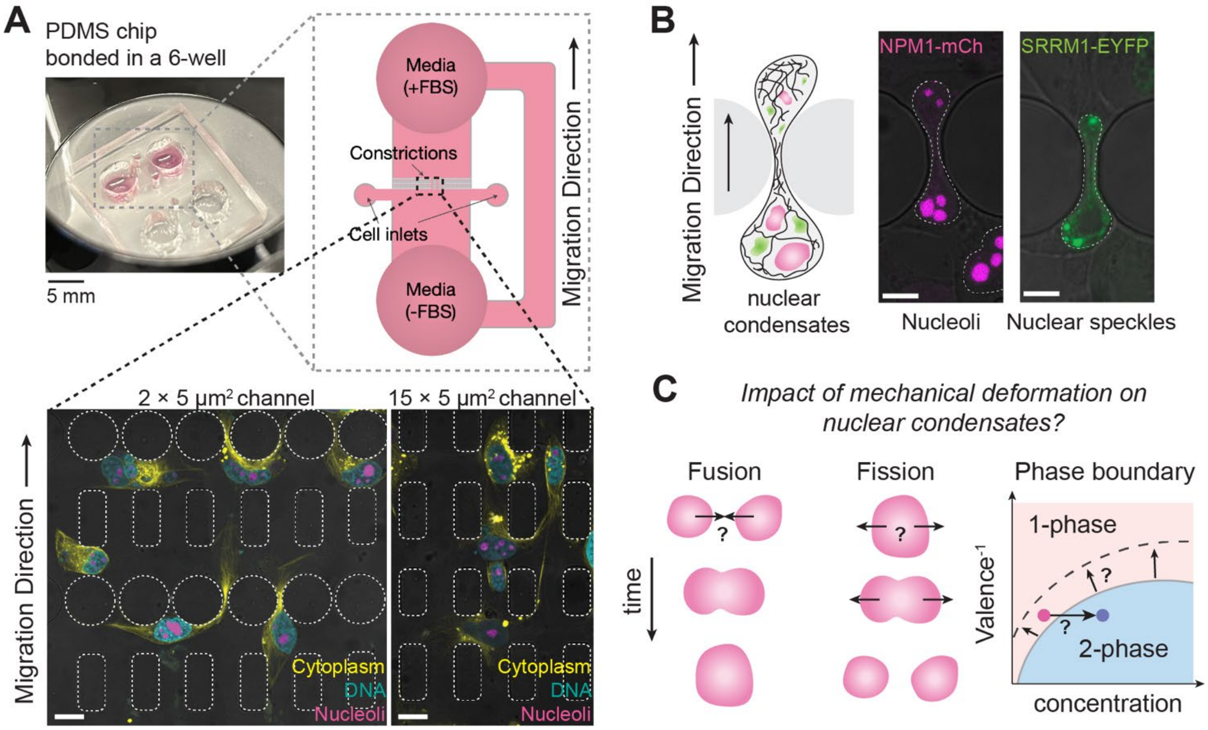


Figure 1: (A, top) Schematics of the microfluidic device in a 6-well plate for studying cancer cell confined migration in the presence of FBS gradient. (A, bottom) Left: confined area with 2-µm wide channel with 5-µm height where the cell nucleus needs to be squeezed through. Right: control area with 15-µm wide channel with 5-µm height where no major deformation of the cell nucleus is observed. Human breast cancer cells MDA-MB-231 with DNA marked by H2B-mGFP (cyan), nucleoli marked by NPM1-mCherry (magenta) and cytoplasm marked by CellBrite dye (yellow). (B) Illustration of nuclear bodies in the nucleus undergoing mechanical deformation, with corresponding stills of representative cells expressing nucleoli marker NPM1-mCherry and SRRM1-EYFP respectively. (C) Schematics of different hypothetical outcomes of mechanical deformation impacting phase-separated assemblies inside cell nucleus. Deformation can result in fusion and fission of nuclear condensates as the nucleus progresses through constriction.

Advisor: Emily C. Davidson

Project Tittle: Dielectric Performance of Polymer Nanocomposite Heterostructures for High Energy Storage Capacitors

Researcher: Jiaen Wu (Graduate)

Sponsorship: Princeton Alliance for Collaborative Research and Innovation (PACRI)

We propose to investigate the role of tailored microstructural orientation and design in polymer nanocomposite heterostructures on the performance of dielectric capacitors for high energy storage applications. Though feature high power density, polymer-based dielectric capacitors demand significant improvement in energy density for advanced energy applications. Aiming to improve the dielectric permittivity ε and energy breakdown voltage Ebd of dielectric capacitors, we leverage advanced processing techniques (eg.3D printing) to fabricate multilayer polymer nanocomposite heterostructure capacitors and control their morphologies and structures at the nanoscale in ways that can increase their energy storage capacity. We have used the profilometer in the cleanroom to characterize the thickness of films.

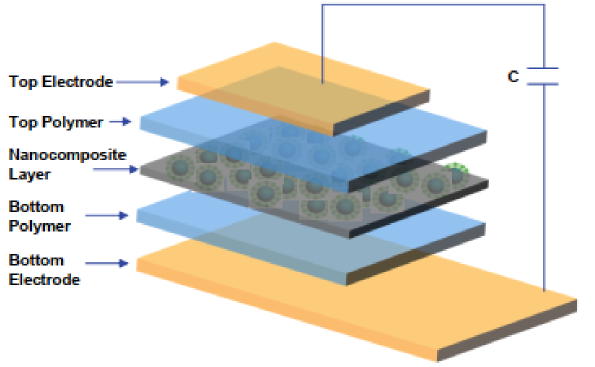


Figure 1. Schematic of proposed multilayer polymer nanocomposite heterostructure capacitor.

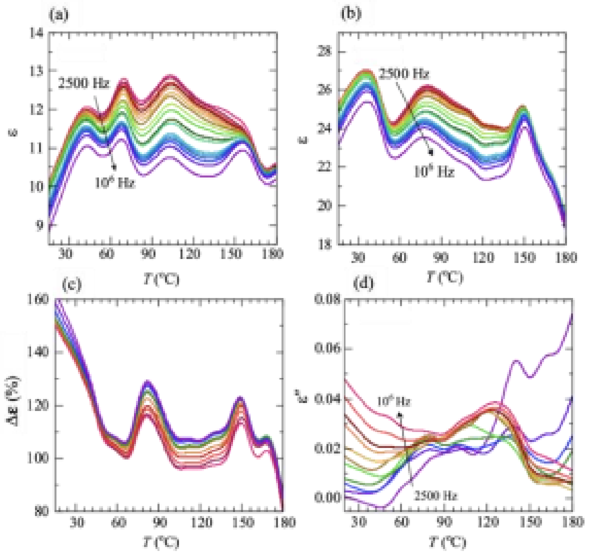


Figure 2. Preliminary data demonstrating temperature dependent dielectric constant of (a) a multilayered PVDF/PMMA/PVDF capacitor (b) a 2D mica interfaced PVDF/2D Mica-PMMA/PVDF heterostructure capacitor. The enhancement of dielectric constant and the loss following incorporation of the 2D nanofiller are depicted in (c) and (d) respectively.

Advisor: Celeste M. Nelson (Chemical and Biological Engineering)

Project Title: DBiT-seq Platform Development

Researcher: Pengfei Zhang (Princeton Postdoc)

Sponsorship: NIH

Spatial omics study is an important tool for developmental biology and tumor biology. DBiT seq is a microfluidic-enabled, highly sensitive platform for spatial omics study with a resolution down to single-cell resolution (10 μm). We used both traditional soft lithography and microPG direct writing and fabricated the microfluidic devices. As a proof-of-concept, we showed the high-resolution spatial transcriptomic mapping of the E8.5 mouse embryo at 10-μm resolution.

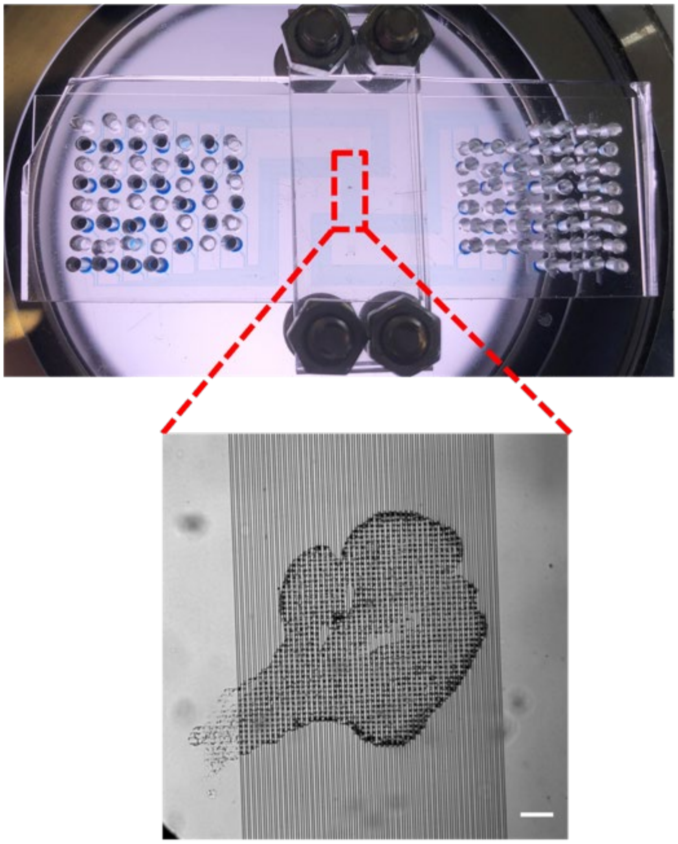


Figure 1: DBiT-seq PDMS chip. Top: microfluidic chip was put on the tissue section and sealed with PMMA clamp. Bottom: the zoom-in figure showed that the PDMS channels were loaded with barcodes for spatial barcoding of embryonic tissue section (scale bar = 100 μm).

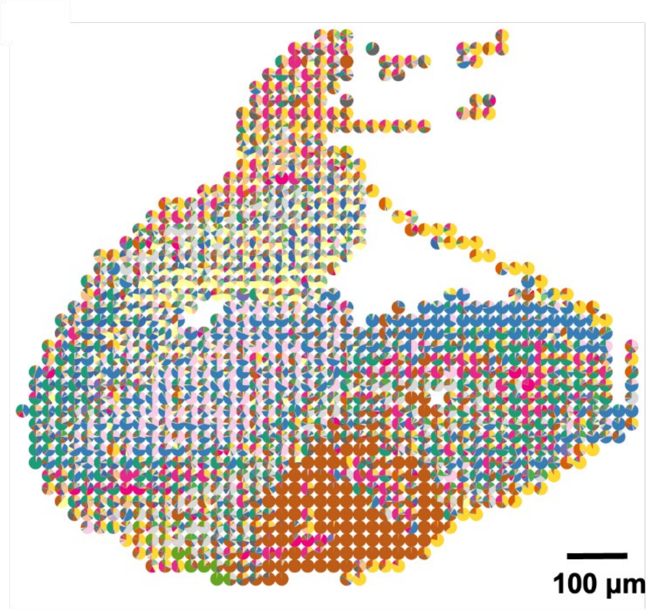


Figure 2: The spatial transcriptomic mapping of E8.5 embryos using 10-μm microfluidic channels. The spatial mapping is accurate and one example is the primitive heart tube structure.

Chemistry

Advisor: Robert J. Cava
Project Tittle: New Substrate for Ta Qubit
Researcher: Chen Yang (Graduate)
Sponsorship: DE-SC0012704

We are sputtering Ta film on a new substrate called LSAT to study the film formation. Due to confidentiality of unpublished results, we can't elaborate more on the current progress and results.

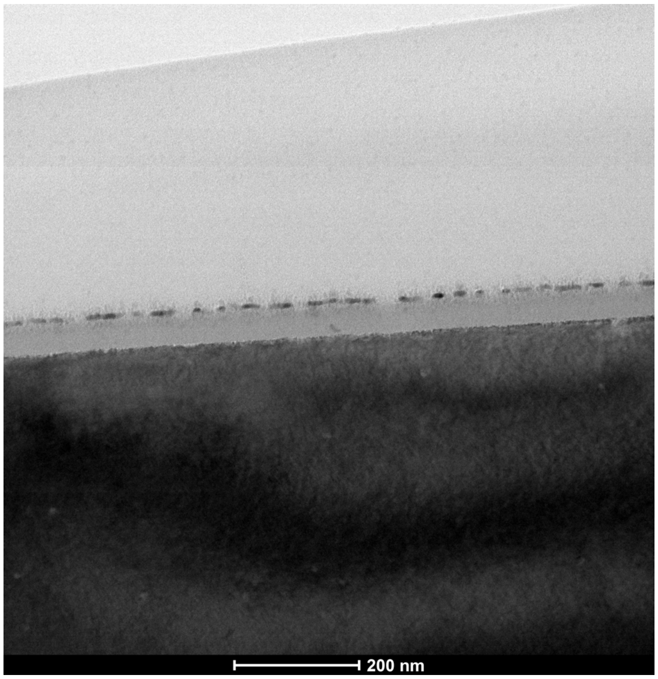


Figure 1: This is a TEM photo showing discontinuous Ta film on LSAT substrate.

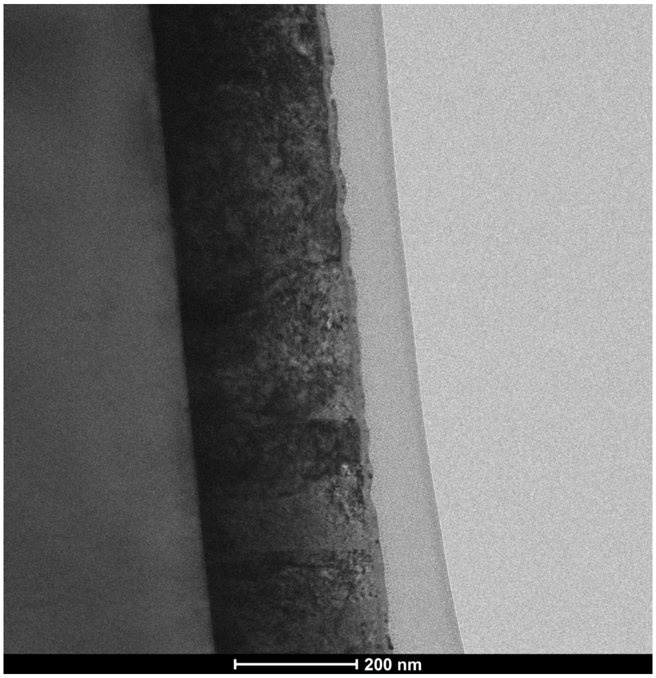


Figure 2: This is a TEM photo showing the cross-section of a continuous Ta film on LSAT substrate.

Advisor: Marissa Weichman
Project Title: Quantum Control of Chemical Reactions via Vibrational Strong Coupling in Optical Microcavities
Researchers: Ashley Fidler (Postdoc), Liying Chen (Graduate)
Sponsorship: Princeton Catalysis Initiative

Quantum control of chemical reactions via light-matter interactions promises to revolutionize transformational chemistry, providing new avenues to generate desirable products or useful energy for a plethora of industrial and research applications. Polaritons, or delocalized hybrid light-matter states that arise due to strong coupling interactions between a molecular ensemble and a confined electromagnetic field of an optical microcavity, may facilitate command over the chemical reaction energetics, dynamics, and products. In this research endeavor, we will build a first-principles understanding of molecular reactivity under vibrational strong coupling by measuring the ultrafast kinetics and dynamics of benchmark condensed phase reactions, including elementary hydrogen abstractions of simple radicals with small molecules. To interrogate these systems under strong coupling, we will design and manufacture robust optical microcavity architectures that permit the measurement of state-dependent chemical dynamics in situ using ultrafast transient absorption spectroscopy. These critical experiments will not only augment the growing body of chemical transformations considered under strong coupling, but also provide tractable model systems for theoretical analysis, informing prospects for using the new degrees of freedom afforded by cavity coupling to steer increasingly complex chemistry.

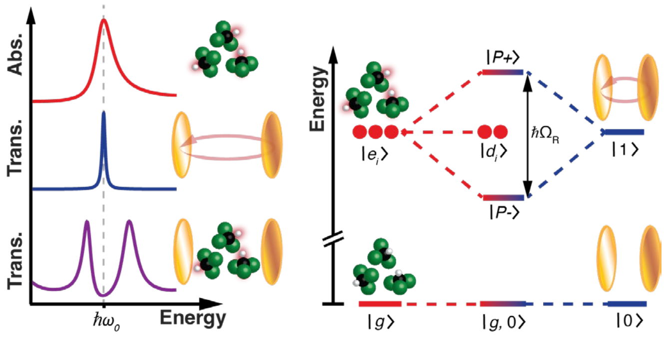


Figure 1: Polariton formation in Fabry-Pérot cavities.

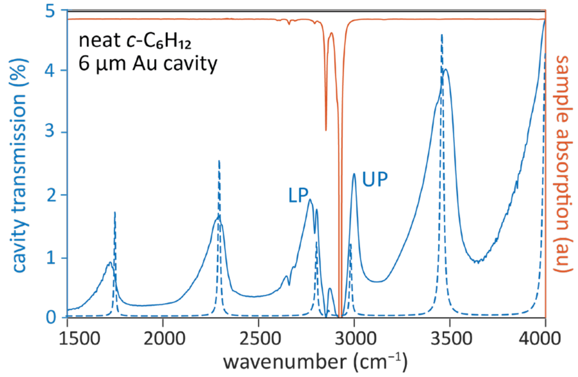


Figure 2: Strong light-matter coupling of the C-H stretch of cyclohexane in a cavity composed of fabricated Au mirrors

Advisor: Marissa Weichman

Project Tittle: Condensed Phase Polaritons – Electronic Strong Coupling

Researcher: Alexander McKillop (Graduate)

Sponsorship: Princeton Catalysis Initiative

At the intersection of photonics and chemistry lie quantum states known as polaritons which may be a new key to manipulate chemical reactions. Polaritons form when a resonant molecular absorption feature and confined electromagnetic field exchange energy at rates that surpass their individual decay mechanisms, resulting in a splitting of the molecular feature into upper and lower polariton states.1 Electronic strong coupling (ESC), marked by polariton formation in molecular electronic transitions, has demonstrated diverse effects such as increased Raman scattering, altered rates of reverse intersystem crossing, and enhanced second harmonic generation efficiency, yet we see it as a tool by which we can control chemistry.1 By fabricating nanometer-scale Fabry-Pérot optical cavities that can support flow chemistry, we aim to study simple photoinduced reactions on ultrafast timescales to pull out state-specific information on how polariton formation alters chemistry. As a classic example of ultrafast photochemistry, the trans-cis isomerization of stilbene is an ideal system to achieve such a goal as it is simple and extremely well-studied. Our work will help inform future experiments by providing a simple molecular system that can be easily modeled to facilitate a concrete explanation of polariton chemistry that does not exist as of yet.

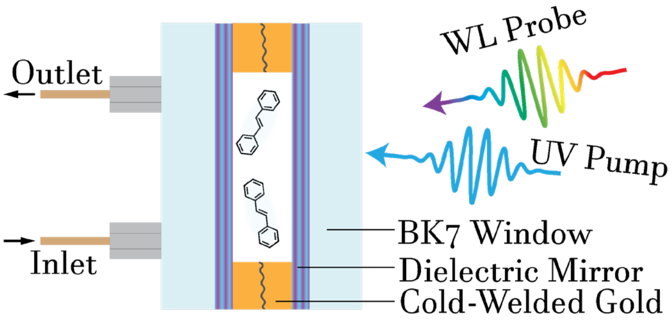


Figure 1: Schematic of the current nano-scale Fabry-Pérot cavity device. The UV pump will initiate the reaction and the white light (WL) probe will be used to track the reaction's progress.

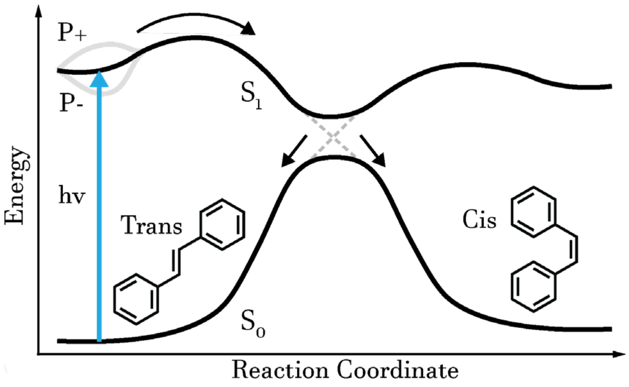


Figure 2: Energy diagram of the trans-cis photoisomerization of stilbene. P+ and P- denote the new upper and lower polariton states that form upon strong coupling to the cavity. We hypothesize that populating these states will alter the excited state lifetimes of the molecules relative to the uncoupled case.

CITATIONS:

Dovzhenko, D. S.; Ryabchuk, S. V.; Rakovich, Y. P.; Nabiev, I. R. Light-matter interaction in the strong coupling regime: configurations, conditions, and applications. Nanoscale 2018, 10 (8), 8. DOI: 10.1039/c7nr06917k.

Advisor: Marissa Weichman
Project Title: Gas-Phase Molecular Polaritons – Exploring Chemistry Under Strong Light-Matter Coupling
Researcher: Jane Nelson (Graduate)
Sponsorship: Startup, National Science Foundation

Polaritons, hybrid quantum states that arise from strong light-matter coupling, are a unique avenue of physical chemistry exploration because of their prospects of altering chemical reactions. In liquid- and solution-phase, strong coupling of molecular vibrational modes to a mode of an optical cavity has changed reaction kinetics and product distribution but the complexity of these environments has impeded the development of mechanistic theoretical understanding. The gas phase is the next frontier for observing and probing these quantum states with careful experimental control and quantum state resolution. To achieve this goal, we have developed a cryogenic buffer gas cell enclosure with a Fabry-Perot optical cavity scheme and probe gas samples in this system with a continuous-wave mid-infrared laser. We use custom Au-coated mirrors to strongly couple to rovibrational states of methane gas in our apparatus. By altering Au layer thickness with different deposition instruments in the MNFC, we can achieve a variety of coupling conditions. We will exploit this tunability to advance polariton chemistry studies toward theoretically-accessible chemical systems.

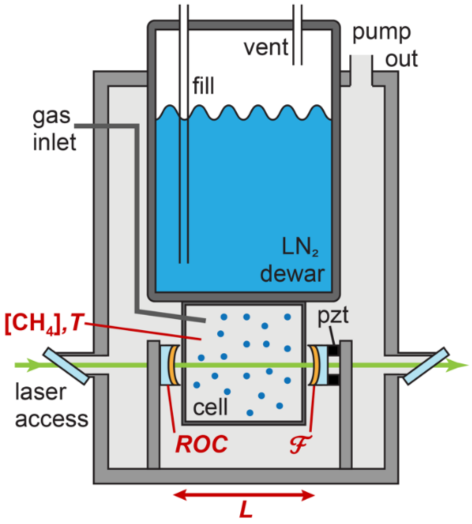


Figure 1: Cryogenic buffer gas cell apparatus used for cavity-coupling a gas-phase molecular sample. The gas cell is housed inside a vacuum chamber and enclosed within a Fabry-Pérot optical cavity to achieve in situ strong coupling. The apparatus permits control over the parameters indicated in red: the number density of methane ([CH4]) and temperature (T) of the intracavity gas, the length (L) and finesse ($\mathcal{F}$) of the cavity, and the radius of curvature (ROC) of the plano-concave cavity mirrors. We alter the finesse of the cavity by changing the thickness of Au deposited on mirror substrates.

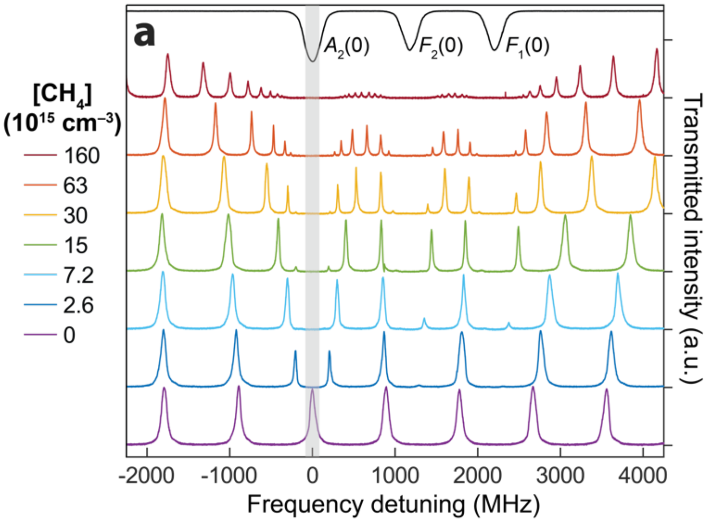


Figure 2: Experimental transmission spectra of a near-confocal Fabry–Pérot cavity with finesse $\mathcal{F} \sim 25$ and length L ~ 8.36 cm, under various intracavity number densities [CH4] at ~115 K (colored traces). Successive spectra are vertically offset for clarity, as is the experimental transmission spectrum of CH4 acquired at ~115 K and [CH4] = 2.0 × 1015 cm−3 (black). In all traces, the cavity mode highlighted in gray is kept locked on resonance with the CH4 ν3 , J = 3 → 4 A2 (0) transition at 3057.687423 cm−1. The frequency axis (300 MHz ≈ 0.01 cm−1) is referenced with this transition corresponding to 0 MHz.

CITATIONS:

A. D. Wright, J. C. Nelson. M L. Weichman; A Versatile Platform for Gas-Phase Molecular Polaritonics; J. Chem. Phys. 159, 164202 (2023)

Advisor: Marissa Weichman

Project Title: Vibrational Polaritons for CO2 Photoreduction

Researcher: Daniel Tajes (Undergraduate)

Sponsorship: Junior Independent Work (JIW) Funding

Fossil fuel dependency has proven to have quite negative effects on both the environment and economy, so we look towards alternative fuel sources and CO2 remediation to lessen these issues. One of the possible solutions is turning CO2 back into fuels through photo- or electrocatalysis. The stable linear nature of CO2 is such that bending it is key to its reduction. In a so-far unrelated branch of chemistry, vibrational polaritons have previously been shown to significantly increase reactivity in reactions. Combining these two concepts, a vibrational polariton tuned to the bending mode of CO2 may have a significant effect on its reactivity with photocatalysts to make hydrocarbons and other reduced organic products.

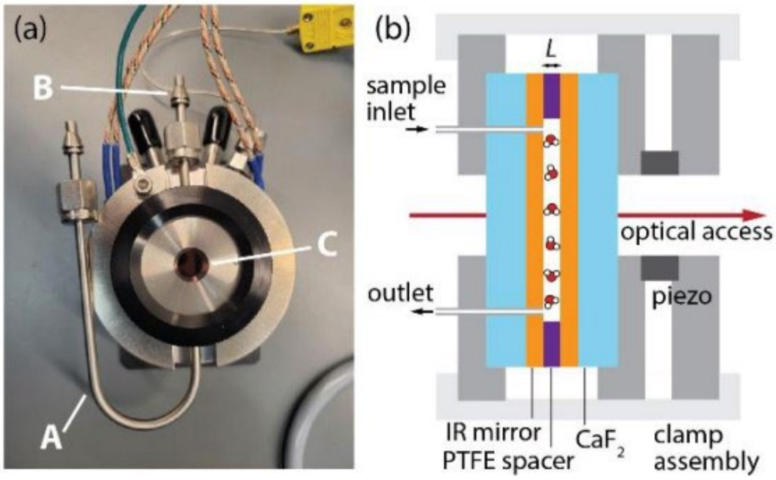


Figure 1: A photograph and diagram of a gas cell

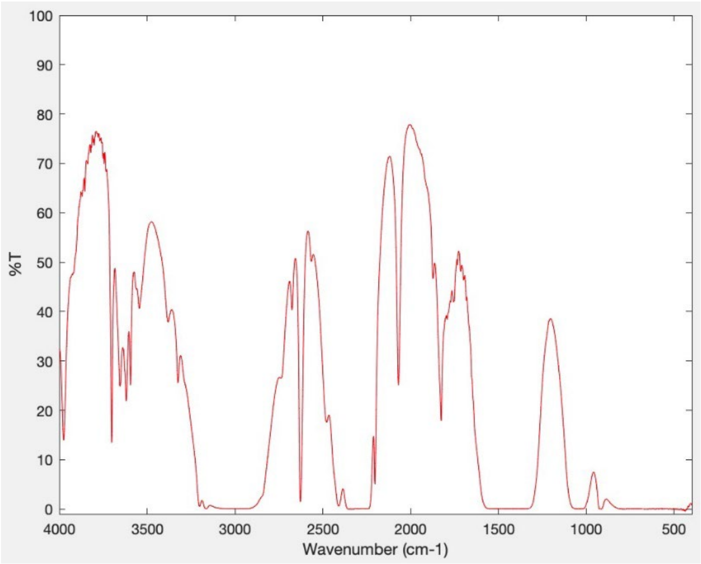


Figure 2: An IR spectrum of CO2-saturated Acetonitrile.

Civil and Environmental Engineering

Advisor: Jyotirmoy Mandal
Project Title: Reimagining Roofs in a Warming World
Researcher: Yung Chak Anson Tsang (Graduate)
Sponsorship: Princeton Innovation Grant - Sustainability of Our Planet

Humans in a warming world urgently need sustainable cooling solutions. We propose to create a novel polymer metamaterial that can enable underlying environments to rapidly cool by directly losing heat to space something that has been unrealized to date. Starting with a new optical design concept, our project will culminate in large-scale demonstrations of performance in real-life scenarios, with early adoption by architects and the construction industry as the intended near-term impact.

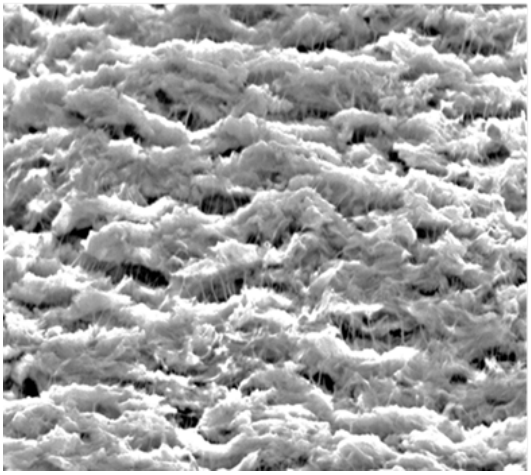


Figure 1: SEM image of a microporous polymer

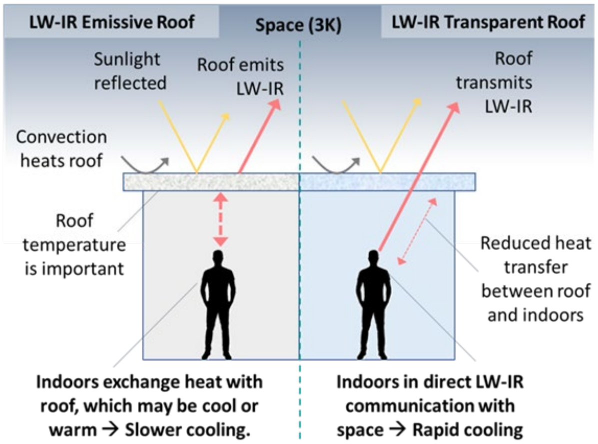


Figure 2: Schematic of the LW-IR transparent roof we are trying to create.

To cool buildings in dense urban environments, it is important for the roof to lose heat to only the view of the sky above, but not gain heat from the warm cityscape that blocks the sky near the horizon. This requires devices and designs with directional emittance, for instance, designs that radiate towards the zenith, but not at high angles from its surface normal.

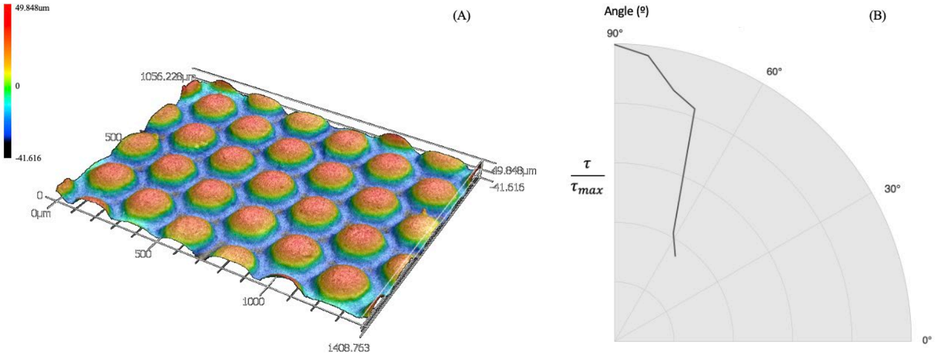


Figure 3: (A) A confocal depth map of the polyethene micro lens array. (B) Preliminary angular transmittance highlighting the angular selectivity of our design.

We have fabricated a microspheroidal lens array made from polyethene (PE) doped with zinc selenide (ZnSe), which has a directional transmittance in the thermal infrared wavelengths (λ~2.5-30 µm) and can efficiently scatters sunlight (λ~0.3-2.5 µm). The ability to implement different optical mechanisms at different wavelength regimes due to the hierarchical structures makes this approach adaptable to a wide variety of use cases.

Advisor: Jyotirmoy Mandal

Project Title: Micro patterned emitters for control of spectrum direction of thermal radiation

Researcher: Mathis Degeorges

Sponsorship: Faculty Startup Funds

We made patterned substrates using vapor deposition technics in MNFC. Our objective was to make micropatterned emitters that enable precise control over the direction of the thermal radiation spectrum. This technology offers passive thermoregulation for buildings in all seasons.

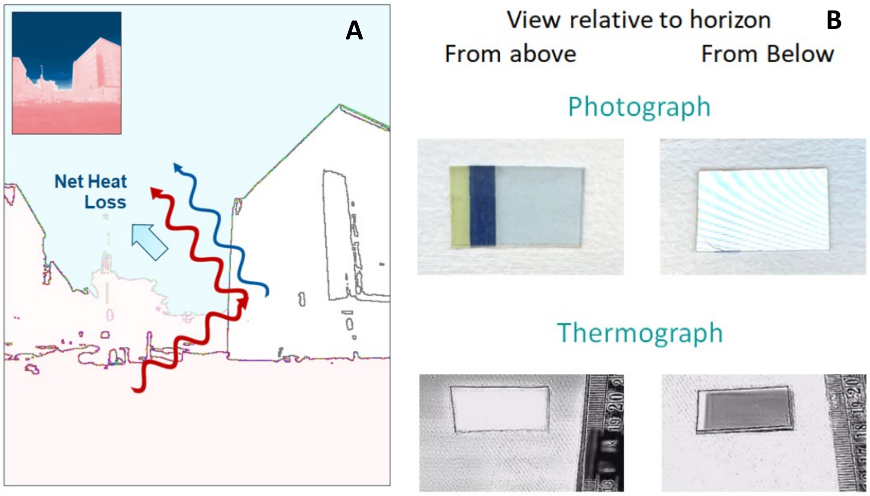


Figure 1: (A) Undesired terrestrial heat gains prevented in summer (B) Visible and Infrared directionality of the micropatterned emitter

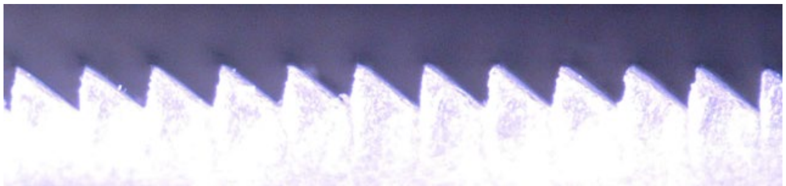


Figure 2: Cross-section image of the micropatterned film taken with a Keyance VHX6000 digital microscope

We've also made an IR integrating sphere—an instrument designed for measuring the diffuse properties of samples. We made the gold coating using a metal sputtering process in MNFC.

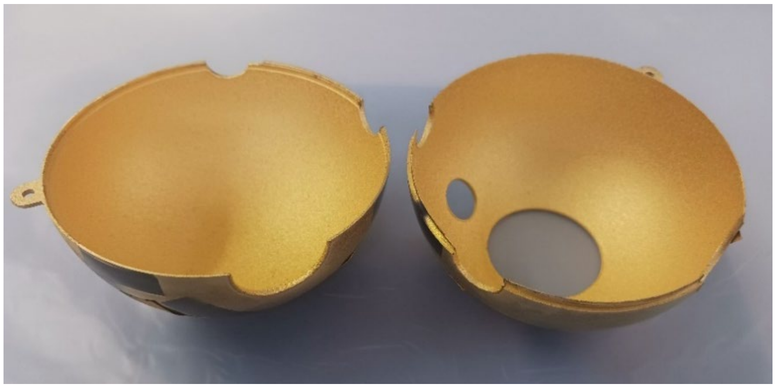


Figure 3: Gold-coating IR integrating sphere

Electrical and Computer Engineering

Advisor: Naveen Verma, James Sturm

Project Title: Diode-based Wireless Systems for Large-Area Electronics

Researcher: Xiaoyang Ma (Graduate)

With large aperture and low cost, thin-film devices integrated on large-scale substrates have demonstrated potentials in future Internet-of-Things (IoT) technologies [1]. However, the cutoff frequencies of thin-film transistors (TFT) are hard to improve due to low mobility and heating effects. Therefore, our goal is to build high-frequency thin-film Schottky diodes, and construct wireless systems upon them. The devices and circuits are fabricated in MNFC with the help of staffs.

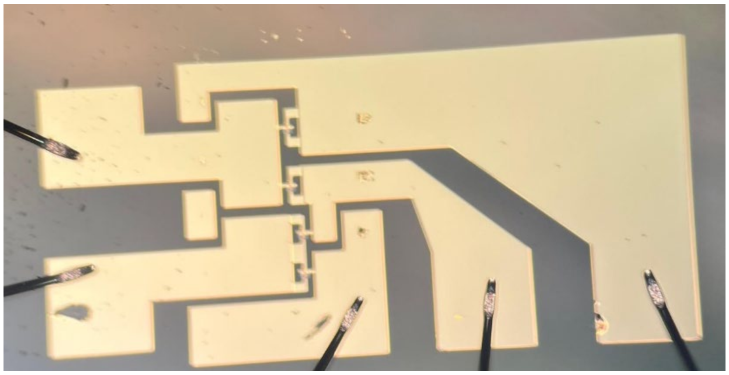


Figure 1: A full-bridge rectifier circuit with 4 ZnO-Au Schottky diodes.

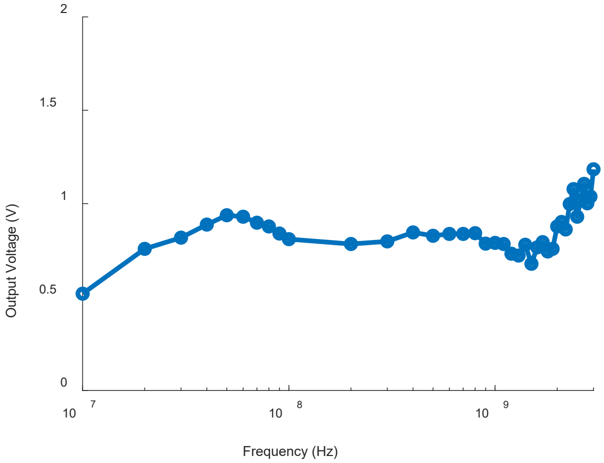


Figure 2: Output voltage vs. frequency of the full-bridge rectifier, with input power of 10 dBm, showing high-frequency operation capabilities beyond 3 GHz.

[1] Y. Ma et al., "Device, Circuit, and System Design for Enabling Giga-Hertz Large-Area Electronics," in IEEE Open Journal of the Solid-State Circuits Society, vol. 2, pp. 177-192, 2022, doi: 10.1109/OJSSCS.2022.3217759.

Advisor: Nathalie P. de Leon

Project Tittle: Chemical Profiles of the Oxides on Tantalum in State-of-the-art Superconducting Circuits

Researcher: Faranak Bahrami (Postdoc)

Sponsorship: The U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Co-design Center for Quantum Advantage (C2QA) under contract number DE- SC0012704

Over the past decades, superconducting qubits have emerged as one of the leading hardware platforms for realizing a quantum processor. Consequently, researchers have made significant effort to understand the loss channels that limit the coherence times of superconducting qubits. A major source of loss has been attributed to two level systems that are present at the material interfaces. We recently showed that replacing the metal in the capacitor of a transmon with tantalum yields record relaxation and coherence times for superconducting qubits, motivating a detailed study of the tantalum surface. In this work, we study the chemical profile of the surface of tantalum films grown on c-plane sapphire using variable energy X-ray photoelectron spectroscopy (VEXPS). We identify the different oxidation states of tantalum that are present in the native oxide resulting from exposure to air, and we measure their distribution through the depth of the film. Furthermore, we show how the volume and depth distribution of these tantalum oxidation states can be altered by various chemical treatments. By correlating these measurements with detailed measurements of quantum devices, we can improve our understanding of the microscopic device losses.

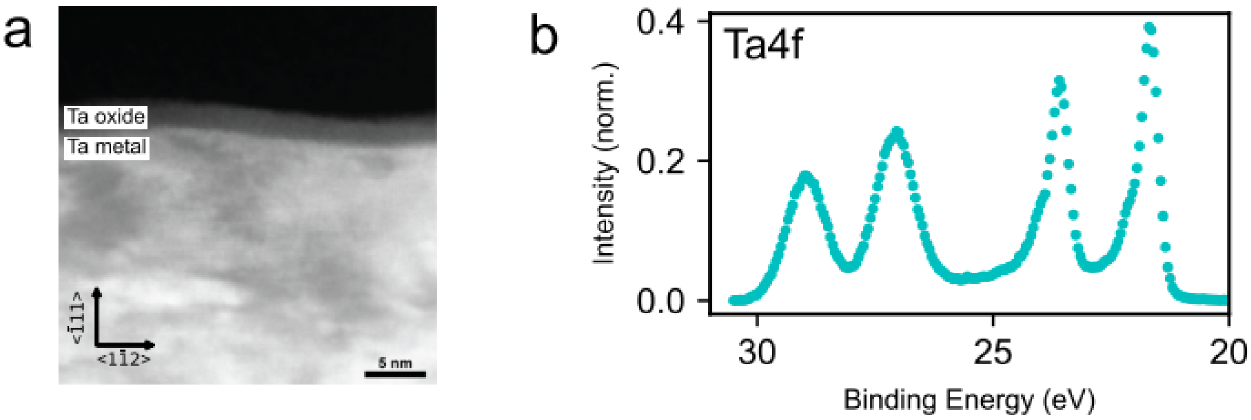


Figure 1: a) High angle annular dark field scanning transmission electron microscope image of the cross-section of a tantalum film on sapphire. The tantalum film has a BCC crystal structure and was grown in the (111) orientation on a c-plane sapphire substrate. An amorphous oxide layer can be seen on top of the tantalum at the tantalum air interface. b) Experimental results of the tantalum binding energy spectrum obtained from X-ray photoelectron spectroscopy (XPS) performed using 760 eV incident photon energy [1].

CITATIONS:

[1] The figures and their captions are from Ref. [McLellan, R. A., Dutta, A., Zhou, C., Jia, Y., Weiland, C., Gui, X., ... & de Leon, N. P. (2023). Chemical profiles of the oxides on tantalum in state of the art superconducting circuits. arXiv preprint arXiv:2301.04567

Advisor: Nathalie P. de Leon

Project Tittle: Diamond Etching and Growth

Researcher: Mu-Chien Wu, (Henry), Associate Research Physicist, Princeton Plasma Physics Laboratory (PPPL)

Sponsorship: DOE

We prepare the diamond samples after the etching process.

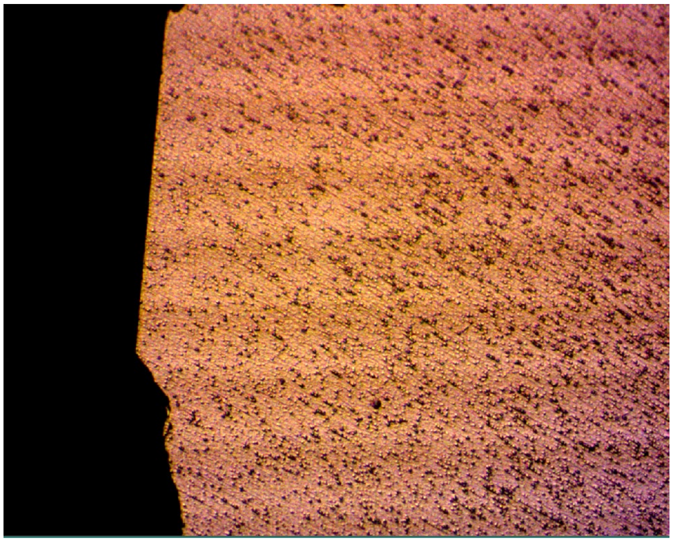


Figure 1: Microscope image of etched diamond at 10x magnification level.

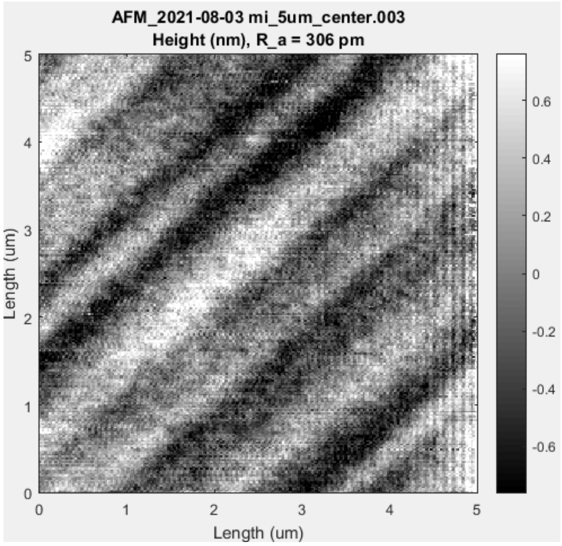


Figure 2: Atomic Force Microscope (AFM) image of etched diamond.

Advisor: Advisor: Nathalie P. de Leon

Project Tittle: Materials for New Josephson Junctions

Researcher: Tunmay K. Gerg (Visiting Scientist)

Superconducting quantum circuits are limited by losses and noise arising from surfaces and interfaces, which can be orders of magnitude worse than for the constituent bulk components. It is widely observed that losses are worse in compact devices and at base temperatures and single photon powers. The possible interfaces that host lossy materials include the Josephson junction itself, which has so far required tunnel barriers made of the native surface oxide of aluminum. This oxide is lossy and a frequent host of two-level systems (TLSs), and current state-of-the-art devices are starting to enter the regime where the Josephson junction may limit the performance of superconducting qubits, motivating a search for alternative materials for Josephson junctions. One possibility is to use different superconducting metals for the junction: metals which are robust to aggressive cleaning processes and metals which have a favorable oxide. For standard fabrication recipes, Josephson junctions are made via a liftoff process, which means the metal must be sputtered at room temperature. Finding metals that meet these requirements are tricky, but one possibility is beta phase tantalum. To determine whether beta phase tantalum would be an improvement, we fabricated coplanar waveguide resonators made from beta phase tantalum. From temperature and power sweeps, we extracted quasiparticle and two level system loss. Some data is shown below:

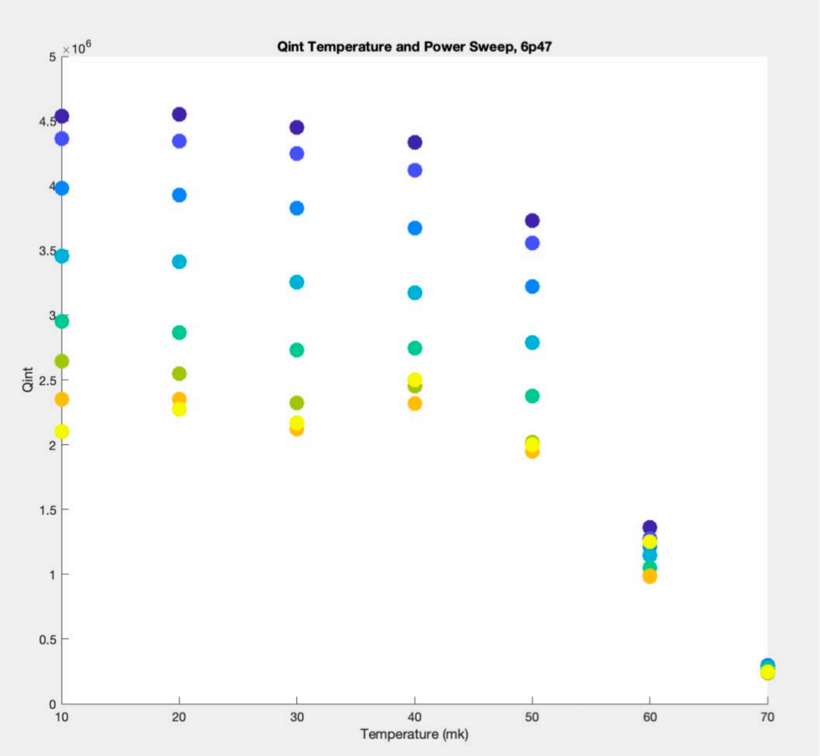


Figure 1: Temperature and power dependence of the internal quality factor of a 6.47 GHz resonator. Purple represents 10dBm power input to dilution fridge, yellow is -60dBm input, and colors in between represent decreases in 10dBm power from the previous.

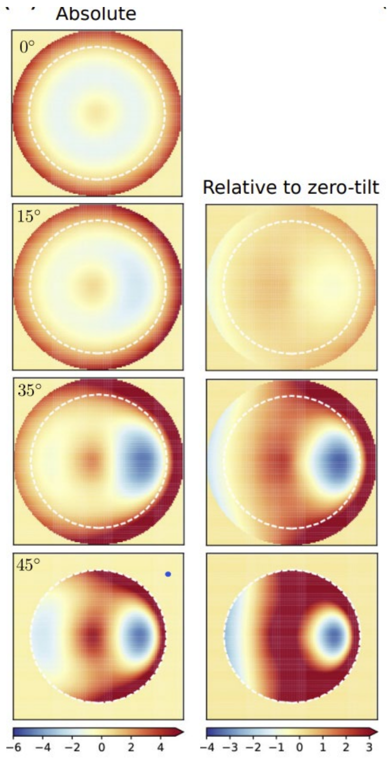
Advisor: Tian-Ming Fu

Project Title: Engineered Metalenses for Aberration Correction in Light Sheet Microscopy

Researcher: Franchesca Doell (Undergraduate)

Sponsorship: McIntosh Independent Work/Senior Thesis Fund

Metasurfaces are a novel technology with the unique ability to manipulate electromagnetic waves in microwave and optical frequencies. In microscopy applications, metalenses, a type of metasurface used in imaging and focusing applications, can be used as a correction technique for aberrations caused by the tilt of a cover glass in open-top light sheet microscopy. The aim of this project is to first identify the aberration caused by the tilt of the cover glass and then to design, fabricate, and test a metalens that corrects for this aberration. With the development of such a metalens, a higher image resolution would be attained in open-top light sheet microscopy as the effects on the image from the aberration would be minimal. This is beneficial as the open-top light sheet microscopy configuration allows researchers to utilize high throughput sample holders while limiting phototoxicity of samples. In the MNFC, the fabrication of this metasurface is completed using electron beam lithography techniques.



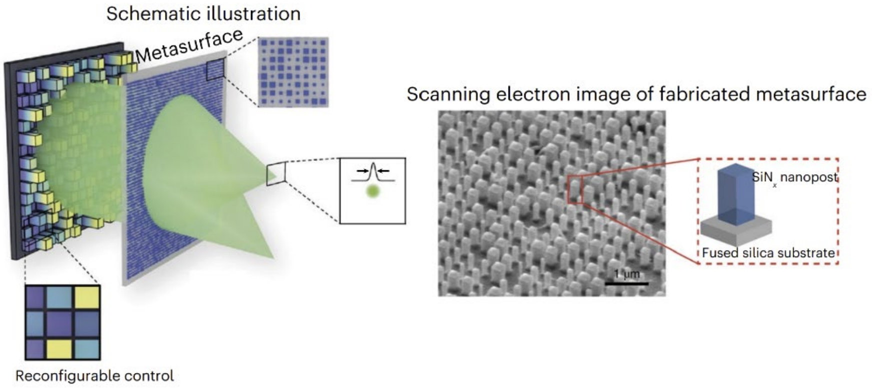


Figure 1: Optical aberrations on the pupil plane caused by the tilt of a coverslip in open-top selective plane illumination microscopy.

Figure 2: A scanning electron image of a metasurface. The different thicknesses of the subunits of a metasurface are used to create a phase profile.

CITATIONS:

Mcgorty, R., Xie, D., and Huang, B. High-NA open-top selective-plane illumination microscopy for biological imaging, Opt. Express 25, 17798-17810 (2017). https://doi.org/10.1364/OE.25.017798.

Arbabi, A., Faraon, A. Advances in optical metalenses. Nat. Photon. 17, 16–25 (2023). https://doi.org/10.1038/s41566-022-01108-6.

Advisor: Tian-Ming Fu

Project Title: Flexible device platform for developmental biology

Researcher: Sara Kacmoli (Postdoc)

Sponsorship: Omenn-Darling Bioengineering Institute, Princeton Catalysis Initiative

In developing organisms, robust and tightly regulated mechanisms govern cell fate, growth and movement in a way that consistently leads to a specific end result. Understanding these complex mechanisms requires tools that allow for systematic, controlled and precise perturbation of the delicate developing environment. We use microfabrication techniques to create free-standing devices composed of soft and flexible materials that can be integrated with biological samples. These devices can be used to encapsulate metal electrodes, magnetic materials, photonic waveguides etc. allowing the study of cell behavior under electric and magnetic fields, optical excitation, or mechanical force. All fabrication and packaging steps for our devices are performed in the MNFC facility.

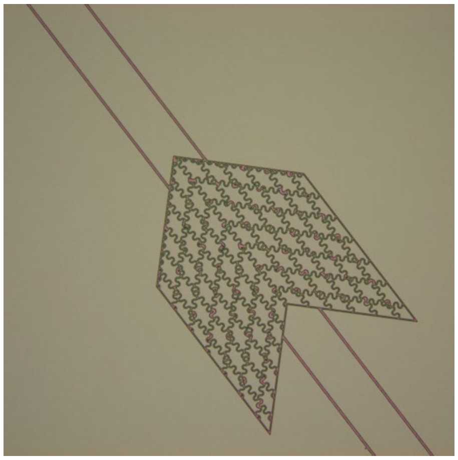


Figure 1: Optical microscope image of a flexible device made of patterned SU8 on a sacrificial layer of nickel on a silicon substrate.

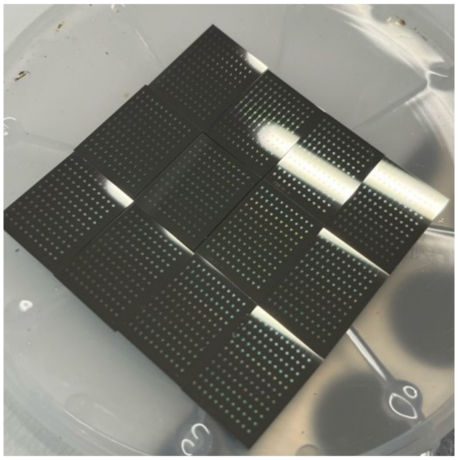


Figure 2: Diced 4-inch silicon wafer with different designs of the flexible devices patterned on a layer of sacrificial nickel.

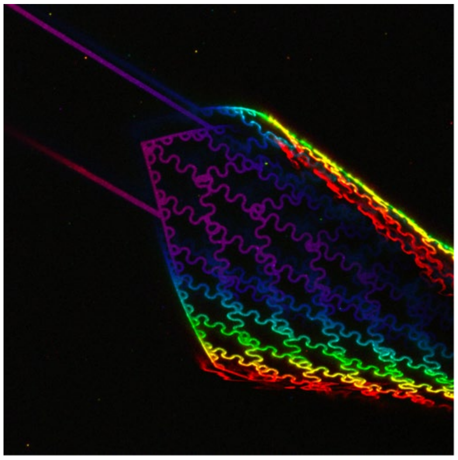


Figure 3: Confocal microscope image of a flexible device fixed in 1% hydrogel which can be used as an approximate for tissue stiffness. The color is a projection of depth.

Advisor: Advisor: Tian-Ming Fu

Project Tittle: Microscale Flexible Devices for Monitoring and Stimulation Developing Brains

Researcher: Fei Liu (Graduate)

Developing multimodal measurement tools that allow us to study biological dynamics in vivo and over long periods of time is highly desired to further our understanding of underlying mechanisms. One particular area that remains riddled with open questions is morphogenesis in developing brains. We aim to develop microscale flexible devices to deliver electronic and photonic sensors into developing brains both for monitoring and stimulation of these samples with a high degree of precision and accuracy.

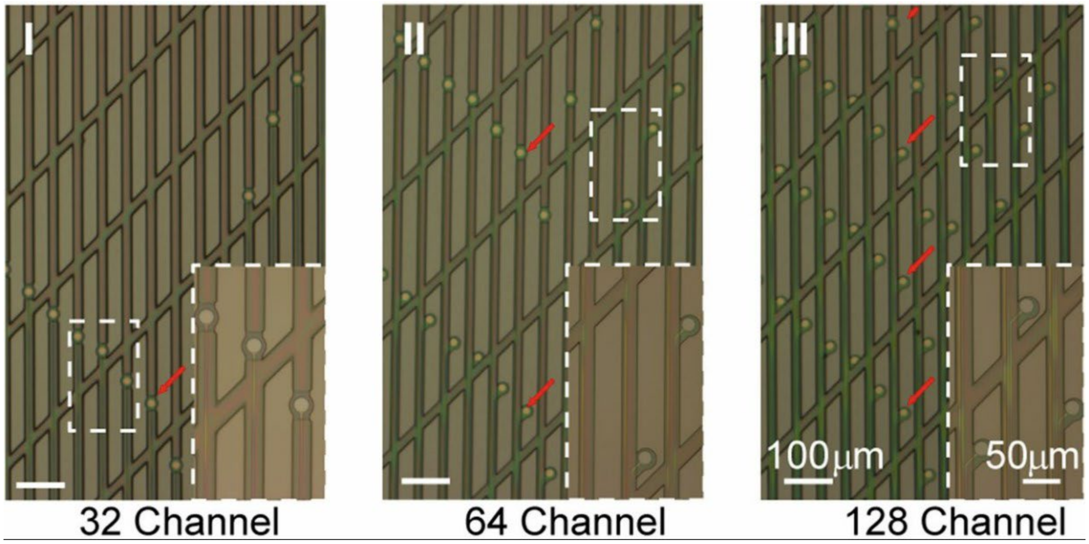


Figure 1: Bright field microscope images showing scaling up of channel number and recording site density via fabricating multiple channels in a single longitudinal element.

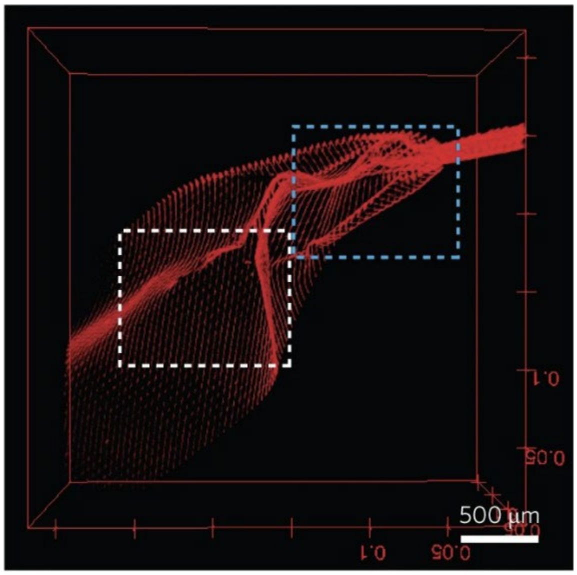


Figure 2: Images of mesh electronics injection through a glass needle ID 95 um into 1 PBS solution.

Advisor: Claire Gmachl
Project Tittle: Disordered Hyperuniform Metamaterials in the Mid-Infrared
Researcher: Manuel Gallego (Graduate)

Disordered Hyperuniform (DHU) structures are a type of metamaterial with potential for image differentiation [1]. They inherit properties from both crystals and liquids, allowing them to possess a photonic band gap (PBG) and spatial isotropy [2,3]. Fabrication of DHU structures uses direct write photolithography to achieve feature sizes of about 1-3 μm, and reactive ion etching to create 6 μm holes inside the substrate by using a dielectric hard mask. Image differentiation is achieved when the source wavelength matches the frequency of the associated DHU PBG [1]. Traditional real time edge detection methods involve a 4F correlator that is constrained to transmission mode near normal incidence angles. In contrast, DHU structures circumvent this by having a notable PBG at angles away from normal incidence, potentially allowing imaging at a wider angle range.

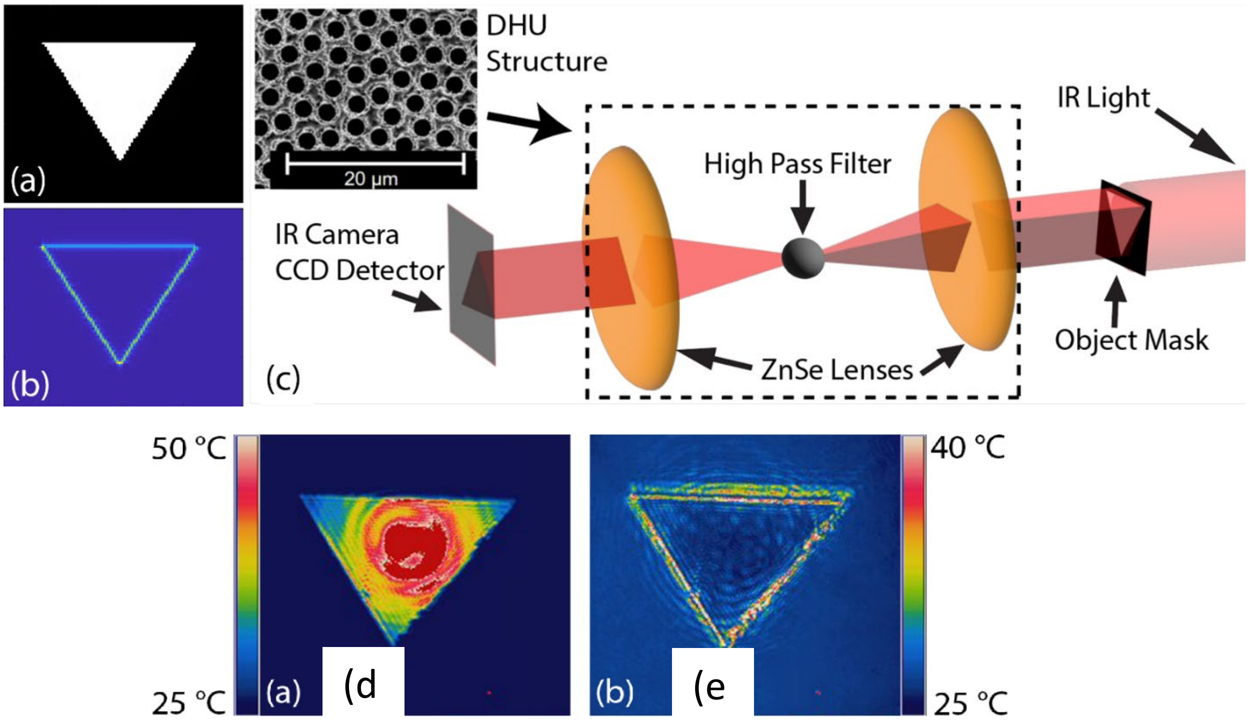


Figure.1 MATLAB digital image processing of an input triangle mask (a) and the convolution with a Laplacian filter to output the edges of the mask (b). (c) shows an image differentiation setup using a 4F correlator consisting of two lenses and a metal sphere acting as a high pass spatial filter. The boxed region corresponds to the components a DHU structure can replace to achieve the same imaging effect. (d) and (e) are the input image and differentiated image, respectively, of the 4F imaging system shown in (c) at wavelength λ = 9 μm.

CITATIONS:
[1] Y. Zhang, Novel Material Engineering in III-IV Semiconductor Platforms: Metamaterials with Quantum Cascade Structures. PhD thesis, Princeton University, 2022; [2] S. Torquato and F. H. Stillinger, "Local density fluctuations, hyperuniformity, and order metrics," Physical Review E, 2003; [3] M. Gallego, S. Kacmoli, Y. Zhang, M. Klatt, and C. F. Gmachl, "Hole-based disordered hyperuniform semiconductor metamaterials for the mid-infrared," in preparation for Optics Express (2024).

Advisor: Claire F. Gmachl

Project Tittle: Coupled Ring Quantum Cascade Laser Biosensor

Researcher: Kathleen Bishop (Undergraduate)

My thesis will focus on coupled ring mid-infrared quantum cascade laser (QCL) biosensors. Significant research has been conducted on quantum cascade ring laser systems, namely by Sara Kacmoli (a recent graduate student under the advisement of Professor Claire Gmachl). The research demonstrates the effectiveness of QC ring laser systems and outlines the systems' potential for on-chip sensing. I plan to build upon this research and investigate coupled ring QC laser biosensors. I have completed an in-depth literature review and am beginning to simulate the biosensor system in KLayout. Finally, I plan to fabricate the system in the MNFC and conduct analysis.

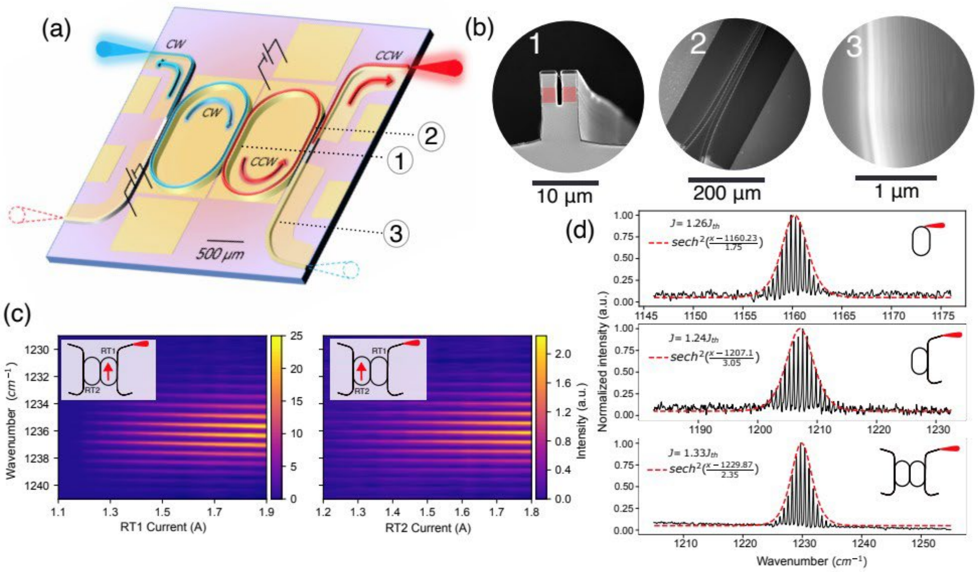


Fig. 1. (a) Diagram of the photonic molecule circuit, illustrating a representative steady-state supermode. Gold pads represent electrodes with top and ground contacts for each element (two pairs per outcoupling waveguide, one pair per racetrack). (b) SEM images detailing (1) a cross section of the evanescent coupler between racetracks (false color marks the active region); (2) a top view of the taper geometry of the couplers; (3) low sidewall roughness. (c) Measurements of lasing spectra at top-right port as a function of pumping current. Note that both racetracks exhibit nearly identical spectra over the entire current range. In the right plot, the right-hand racetrack is unpumped and serves as a passive waveguide coupling the optical output of the left-hand racetrack to the output port. (d) Measured spectra from three different devices: standalone racetrack, racetrack coupled to a waveguide, and photonic molecule system as shown in (a). Note that the comb structure remains intact in all three configurations. The center wavelengths and free spectral range (FSR) values are different because these are devices of different sizes fabricated on different wafers.

CITATIONS:

[1} Kacmoli, S., Sivco, D. L., & Gmachl, C. F. (2023). Photonic molecule based on coupled ring quantum cascade lasers. arXiv preprint arXiv:2304.11484. [2]Kacmoli, S., Sivco, D. L., & Gmachl, C. F. (2022). Unidirectional mode selection in bistable quantum cascade ring lasers. Optics Express, 30(26), 47475-47484.

Advisor: Stephen A Lyon
Project Tittle: Coupling Electron Spin to Superconducting Resonator
Researcher: Weiheng Fu (Graduate)
Sponsorship: DOE

My project involves fabricating resonators coupled to electrons on liquid helium, with the ultimate goal of performing electron spin resonance with the system. Everything except for Nb and NbSi deposition was done in MNFC.

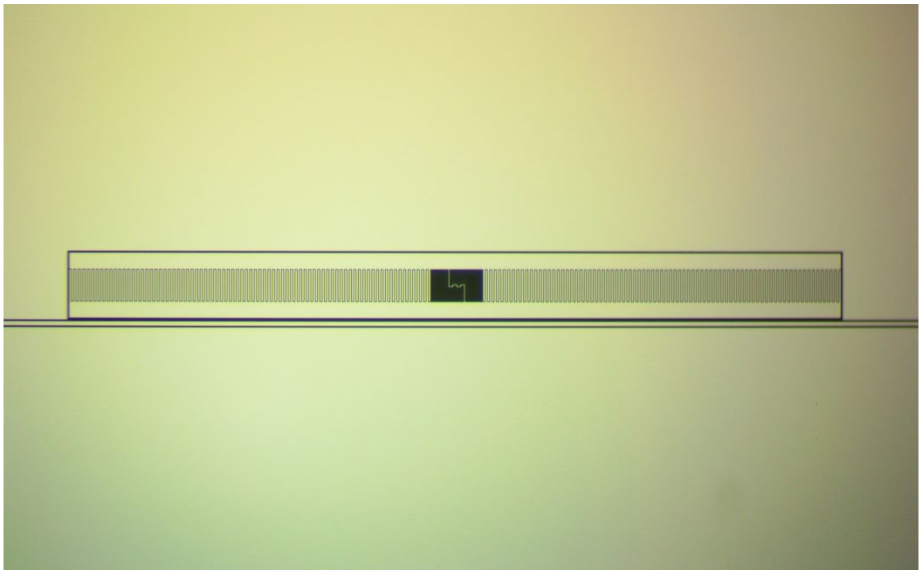


Figure 1: One Layer Nb lumped LC resonator coupled to CPW line.

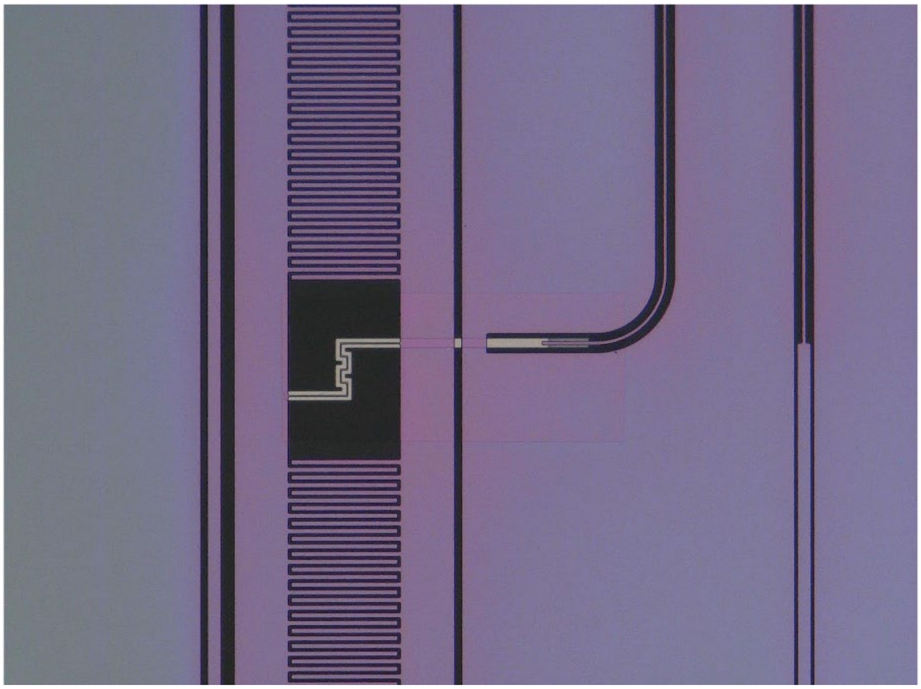


Figure 2: A two metal layer device with NbSi as bias underneath the inductor. The metal layers are separated by thin layer of ALD.

Advisor: Andrew A. Houck

Project Title: Flat-Band Localization and Interaction-Induced Delocalization of Photons

Researchers: Jeronimo Martinez (Graduate), Christie Chiu (Postdoc), Matthew Molinelli (Graduate), Basil Smitham (Graduate)

Sponsorship: NSF Quantum Leap Challenge Institute for Robust Quantum Simulation 2120757, ARO MURI W911NF-15-1-0397, Princeton Center for Complex Materials NSF DMR-1420541 and NSF GRFP DGE-2039656

A recent project we worked on and recently published [1] was exploring the dynamics of particles in lattices. To do so, we use superconducting qubits where the qubits play the role of lattice sites and the microwave excitations of the qubits take the role of particles. By adding synthetic magnetic fields, the particles acquire phases that lead to destructive interference leading to localized dynamics. With multiple interacting particles, the acquired phase can change and lead to constructive interference and allow for fully delocalized dynamics. We explored this physics using four superconducting qubits where the device was fabricated in MNFC. A photo of the device is shown in Figure 1.

Since then, we have developed a recipe in MNFC to introduce aluminum airbridges into our devices based on Ref [2]. Airbridges reduce spurious modes in coplanar waveguides and allow transmission lines and waveguides to cross over each other. This will enable us to develop much more complicated chip designs in the future. Images of the airbridges we created are shown in Figure 2.

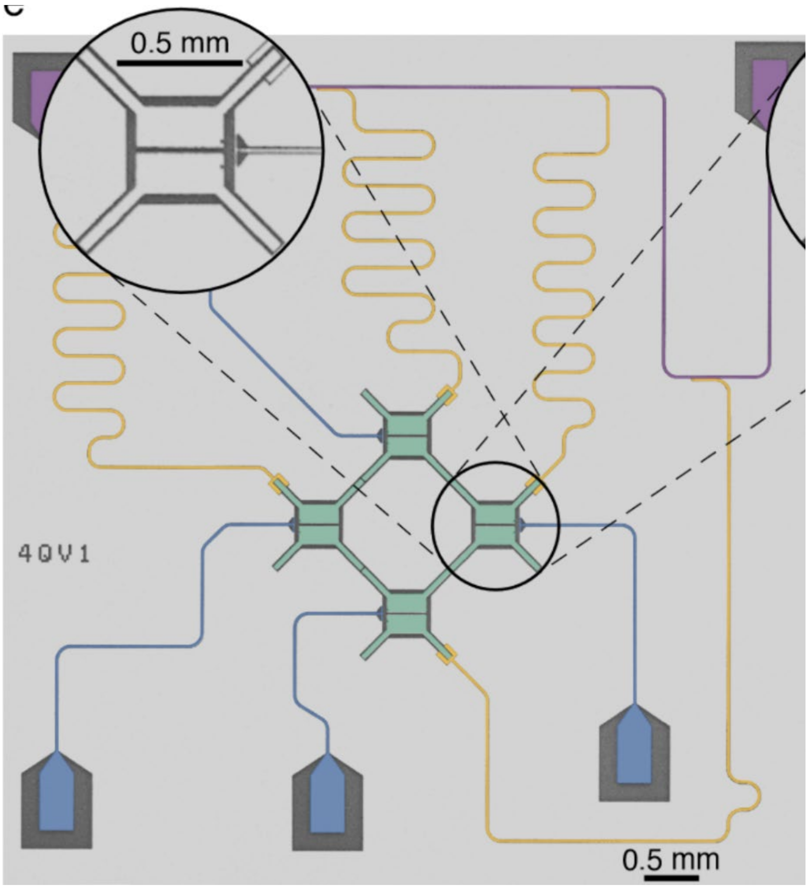


Figure 1: Device image of four superconducting qubits (green) coupled in a ring configuration. Readout cavities are shown in yellow and qubit control lines in blue. This device was used to explore the localized dynamics of particles in a synthetic magnetic field and the subsequent delocalized dynamics once multiple interacting particles are introduced.

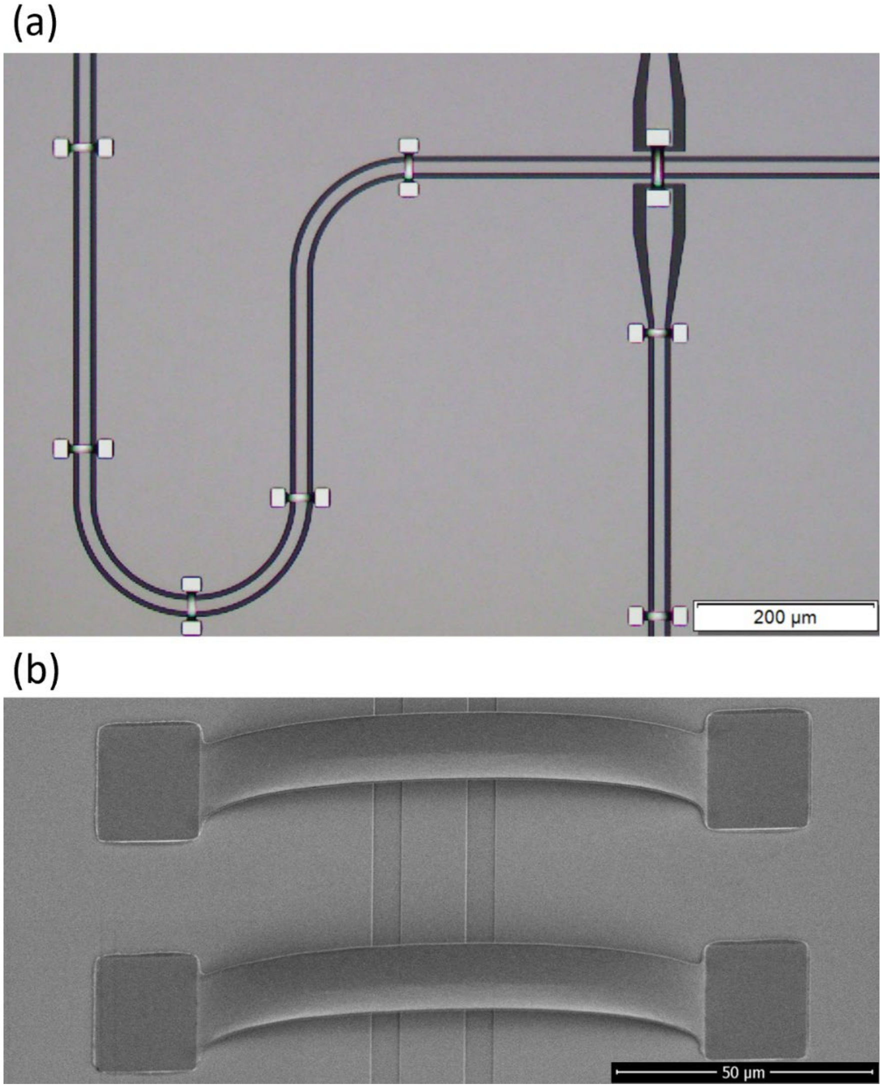


Figure 2: Airbridges developed for superconducting devices. (a) Microscope image of a device with superconducting metal (gray), sapphire (black), and aluminum airbridges (silver). The bridges short the ground planes of the coplanar waveguides and are used to "jump" two lines over each other (upper right). (b) SEM image of two airbridges over a coplanar waveguide.

CITATIONS:

[1] Jeronimo G. C. Martinez et al. Flat-band localization and interaction-induced delocalization of photons. Sci. Adv.9,eadj7195 (2023)

[2] Chen, Zijun et al. "Fabrication and characterization of aluminum airbridges for superconducting microwave circuits." Applied Physics Letters 104 (2013): 052602.

Advisor: Andrew A. Houck
Project Title: Understanding Dielectric Loss in Fluxonium
Researcher: Parth Jatakia (Graduate)
Sponsorship: C2QA, DOE

Past generations of high-coherence fluxonium qubits suggest dielectric loss as the dominant source of T_1 noise. A deeper dive into material characteristics and design choices is necessary to understand the sources of the dielectric losses. We operate the fluxonium in a new parameter regime to investigate the electric field distribution and the entailing dielectric-loss mechanisms.

Using tantalum, an improvement in $Q_{\text{dielectric}}$ has been demonstrated for transmons. Using a similar recipe if one fabricates a fluxonium, one hopes to see improvement. However, this requires the electric field structure to be the same as a Transmon which is a huge assumption. The goal is to examine the dielectric loss mechanisms for a general electric field distribution.

To pinpoint the source of dielectric loss, the ability to simulate the electric field is necessary. Fluxonium at half flux provides an interesting challenge in doing so because the harmonic oscillator approximation cannot be taken. Using a two pronged approach of improving on theory and better empirical understanding we try to bridge the gap.

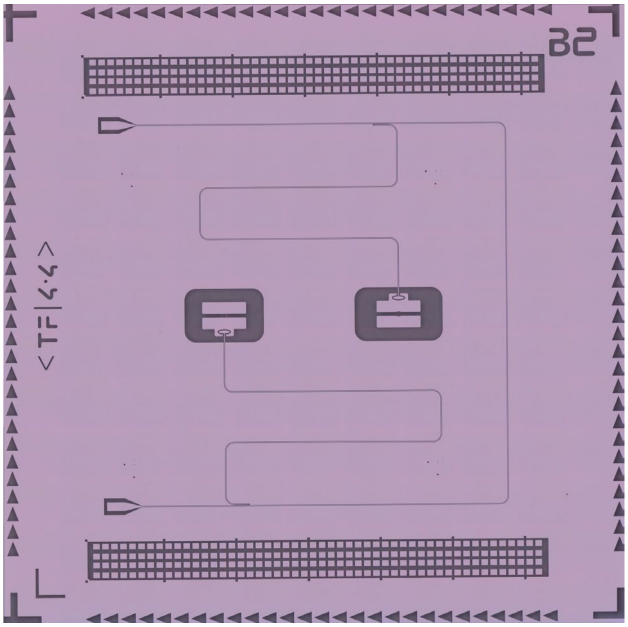


Figure 1: Optical Image of the chip where two fluxonium are coupled to a resonator individually which are multiplexed to a feedline for readout.

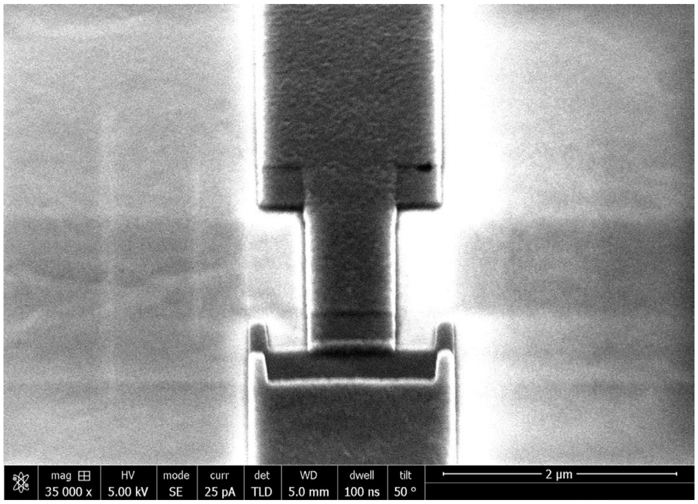


Figure 2: SEM Image of a Dolan Josephson Junction. One can see the two layers of superconducting region of Al. The Josephson Junction here is created with Al-AlOx.

Advisor: Antoine Kahn
Project Title: Characterizing the Concentration-Dependent Conductivity of n-doped WS_2
Researcher: Colin Brown (Undergraduate)
Sponsorship: Schmidt Fund, Lidow Independent Work/Senior Thesis Fund

Modern daily life is heavily dictated by semiconductors, yet silicon is approaching its limit in being able to support more advanced microchips and sustain Moore s Law. In response, 2D materials - atomically thin sheets that show special properties compared to their bulk states - are seen as possibilities for post-silicon chips, and a class of materials called 2D transition metal dichalcogenides (TMDs) are highly promising for this goal.

This project focuses on WS_2 and apply a novel organic n-dopant called (pentamethyl cyclopentadienyl) (1,3,5-trimethylbenzene) ruthenium dimer (RuCp*Mes)2 through evaporation doping. To characterize this doping reaction, this project utilized the MNFC to create micron-scale devices that can be used to measure the conductivity of both the doped and undoped WS_2. Understanding the effectiveness of this doping technique and the relationship between the doping concentration and performance will help advance this material towards application. The synthesis portion of this work will partner with Prof. Saien Xie, whose lab specializes in a technique called metal-organic chemical vapor deposition (MOCVD). The prepared films are brought to the MNFC for using lithography, etching, and deposition instruments to form the contacts pictured below.

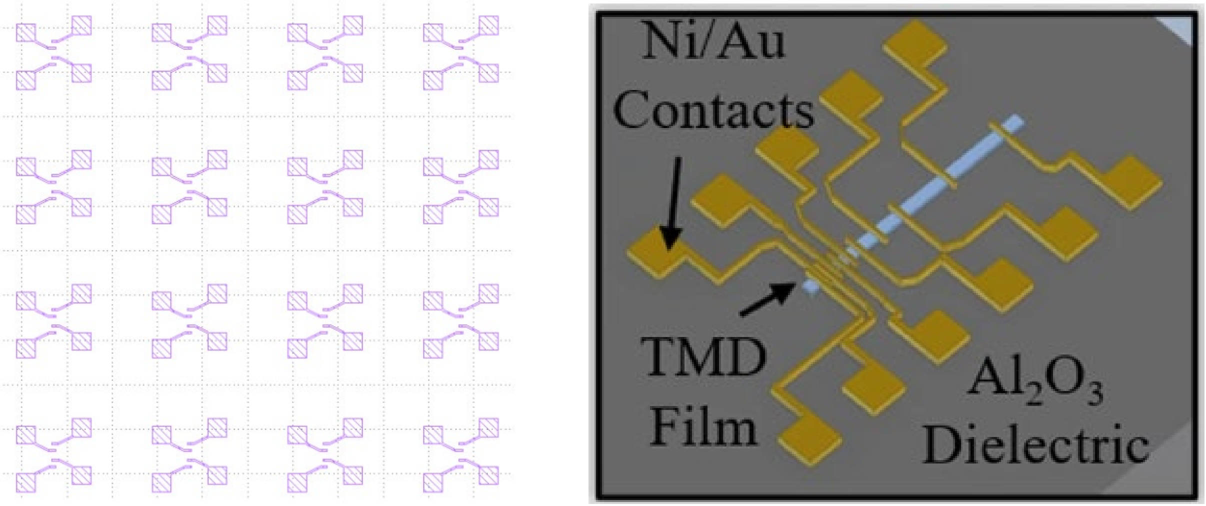


Figure 1: Pattern for electrodes deposited on WS_2 (left), and reference design for 4-point conductivity device on a TMD sample (right)

CITATIONS:
Radisavljevic, B., Radenovic, A., Brivio, J. et al. Single-layer MoS_2 transistors. Nature Nanotech 6, 147–150 (2011). https://doi.org/10.1038/nnano.2010.279

Sebastian, A., Pendurthi, R., Choudhury, T.H. et al. Benchmarking monolayer MoS_2 and WS_2 field-effect transistors. Nat Commun 12, 693 (2021). https://doi.org/10.1038/s41467-020-20732-w

Advisor: Mansour Shayegan

Project Title: Probing Exotic Phases of Two-Dimensional Hole Systems

Researcher: Casey Calhoun (Graduate)

Sponsorship: Schmidt

At low temperature and under a perpendicular magnetic field, two-dimensional electron and hole systems have been observed to form a variety of exotic quantum states. Thanks to recent advances in growth techniques, the fabrication of high-quality two-dimensional charge carrier systems with record-breaking high mobilities is now possible. This has enabled the observation of exciting new features including an unusual even-denominator fractional quantum hall state at filling factor 3⁄4. Measurements in these ultra-high-quality samples have also revealed a new feature: oscillations at extremely low magnetic fields. These oscillations exhibit a distinctively lower frequency than the well-known Shubnikov-de Haas (SdH) oscillations and appear to continue down to very low fields where the SdH oscillations have disappeared. Further study of these oscillations via low-temperature magneto-transport measurements of similar high-mobility, two-dimensional hole systems should help to characterize these features in order to determine their physical mechanism.

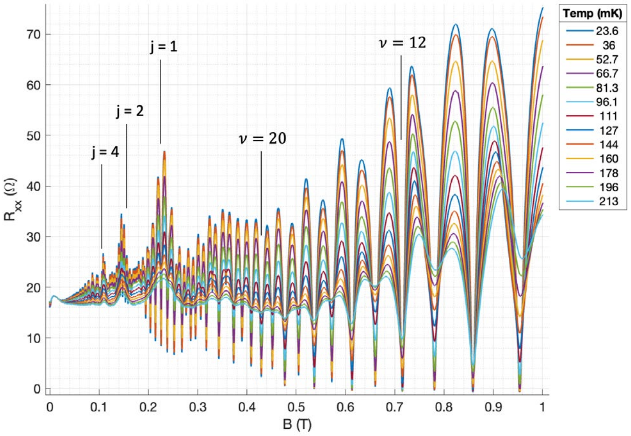


Figure 1: Low field magneto-resistance oscillations for ultra-high mobility, 2D hole system in a 20nm wide GaAs quantum well for a variety of different temperatures. The expected SdH oscillations exist down to roughly 0.2T at lower temperatures before they die out (this occurs at slightly higher field at higher temperatures). The anomalous low-field oscillations show up around 0.25T.

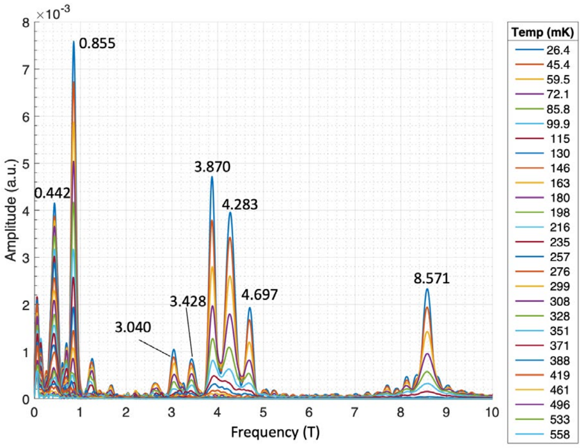


Figure 2: Fourier analysis of the low field portion of the magneto-resistance oscillations for the same sample shown in figure 1. In addition to the expected higher frequency peak corresponding to the carrier density of the sample, many other peaks can be observed including the two spin-split frequencies and various combination frequencies.

CITATIONS:

(1) Yoon Jang Chung, C. Wang, S. K. Singh, A. Gupta, K. W. Baldwin, K. W. West, R. Winkler, M. Shayegan, and L. N. Pfeiffer, Record-quality GaAs two-dimensional hole systems, Phys. Rev. Mater. 6, 034005 (2022).

(2) C. Calhoun, C. Wang, E. Chung, K. Baldwin, L. Pfeiffer, and M. Shayegan, Anomalous magneto-oscillations at very low magnetic fields in ultra-high-mobility GaAs two-dimensional hole systems, Bulletin of the American Physical Society (2023).

Advisor: James C. Sturm
Project Title: Silicon-Based Quantum Computing: Enhancement-Mode Undoped 2DEG
Researcher: Zoe Cyue (Graduate)
Sponsorship: Princeton University Internal Funds

Single-electron quantum dot (QD) devices fabricated from Si/SiGe two-dimensional electron gases (2DEGs) are attractive due to the weak hyperfine interaction, weak spin-orbit coupling, and resulting long relaxation time. Recently, a metal-oxide-semiconductor (MOS) gated undoped enhancement-mode Si/SiGe heterostructure was demonstrated as a promising approach to realize a single-electron QD in silicon due to its capability to tune the 2D electron density (n2D) in a strained Si 2DEG to a very low level, which in turn facilitates the process to isolate a single electron. Currently, the main challenge of this Si/SiGe QD used in quantum computing is its small valley splitting since the intervalley scattering degrades spin coherence and operation fidelity. To resolve this problem, we grew ultra-flat quantum well layers with surface roughness of below 0.2 nm using our home-built ultra-high vacuum CVD chamber. The layer structure is Si substrate/ SiGe graded buffer/ SiGe relaxed buffer with 30% Ge content/ Si buffer/ SiGe/ strained Si/ SiGe/ Si cap. To achieve the goal of growing an ultra-flat quantum well layer with low oxygen contamination, our efforts include performing a chamber bake-out process before the growth, dipping the sample into 1% dilute HF solution for H-passivation, pre-coating the chamber with Si, pumping the loadlock chamber to 5×10^{-7} torr before chamber transferring, and optimizing the flow rate of hydrogen during the pre-baking process. Figure 1 and 2 show the AFM image and the SIMS analysis of a test structure (Sample #7008). The layer structure is Si (80 nm)/ Si substrate. We achieved a RMS roughness of 3.63 nm and O contamination is ~10^{19} cm^{-3} at the grown Si layer and ~10^{21} cm^{-3} at the regrown interface. Our next steps to improve the film quality are performing chemical-mechanical polishing process (CMP) on the Si substrate, optimizing the pre-baking time, and changing the silane (gas precursor) purifier to lower contamination.

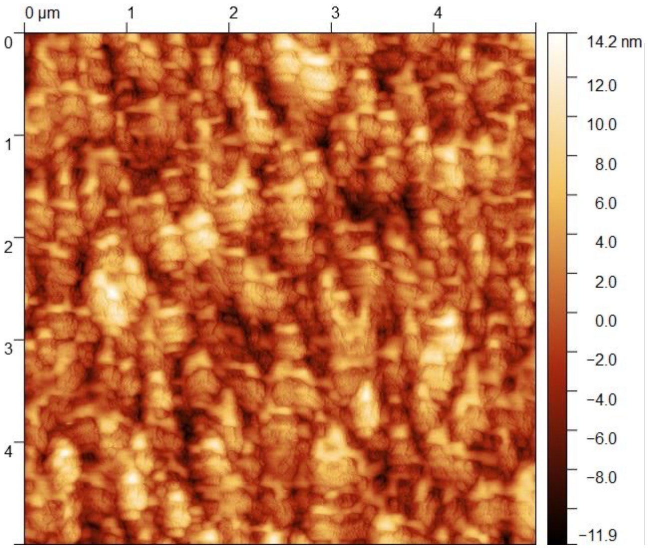


Figure 1: The AFM image of Sample #7008 (Bruker Dimension AFM (Nanoman). The layer structure grown by our UHV-CVD system is Si (80 nm) / Si

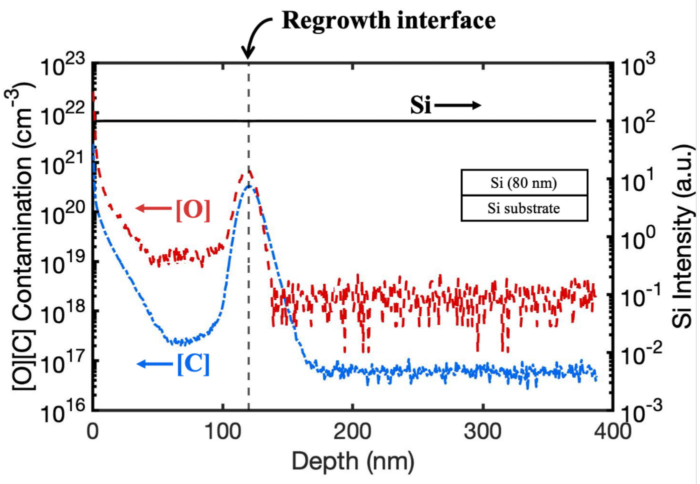


Figure 2: The SIMS analysis of Sample #7008 done by EAG laboratory. The layer structure is shown in inset.

Advisor: James C. Sturm

Project Title: Thermal Characterization of High-Performance ZnO Thin-Film Transistors

Researcher: Nicholas Fata (Graduate)

Sponsorship: Internal

This project is concerned with the fabrication of self-aligned, passivated ZnO thin-film transistors (TFTs), using plasma- enhanced atomic layer deposition (PEALD), for use in large-area electronics (LAE) applications. In LAE, devices are typically fabricated on thermally insulating substrates, such as glass. This means that any heat generated by the device during operation largely remains confined within the device. This heat generation becomes more problematic for TFTs with small TFT channel lengths (such as the one in Fig. 1 with length ~1.4µm), as drain current increases, which increases the power in the channel during operation ($P = I_{DS}V_{DS}$). We aim to gain a quantitative understanding of this "self-heating" effect and how temperature impacts TFT operation and performance, which could ultimately lead to higher frequency operation. We accomplish thermal characterization via a double gate pad structure, shown in Fig. 2, in which device temperature can be evaluated via the change in the resistance between the pads. In the MNFC, we perform most TFT fabrication steps, including metal deposition, photolithography, wet etching, and photomask fabrication.

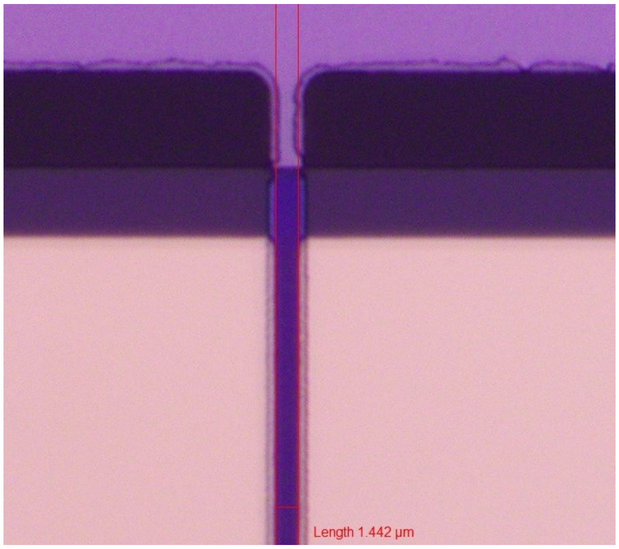


Figure 1: Microscope image of a closeup of a typical self-aligned TFT gate. For this particular thin-film transistor, the optically measured channel length is ~1.4µm. With smaller channel lengths comes greater performance and therefore self-heating when on.

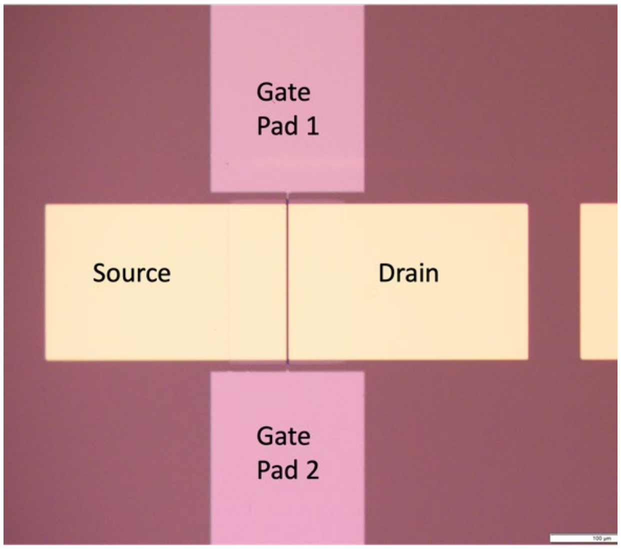


Figure 2: Microscope image of a self-aligned passivated ZnO thin-film transistor with two gate pads for in-situ device temperature measurement.

CITATIONS:

Y. Ma et al., "Device, Circuit, and System Design for Enabling Giga-Hertz Large-Area Electronics," in IEEE Open Journal of the Solid-State Circuits Society, vol. 2, pp. 177-192, 2022, doi: 10.1109/OJSSCS.2022.3217759.

Advisors: James C. Sturm, Naveen Verma, and Sigurd Wagner
Project Tittle: High-Performance Radio-Frequency Devices based on Large-Area Electronics
Researcher: Yue Ma (Graduate)

Sponsorship: This work was supported in part by the Center for Brain-Inspired Computing, one of six centers in JUMP sponsored by DARPA, and in part by the Princeton Program in Plasma Science and Technology.

This work demonstrates high-performance radio-frequency devices based on Large-Area Electronics (LAE). In terms of active devices, unity power gain frequency f_{MAX} exceeding 3 GHz is demonstrated in photolithography-patterned and self-aligned zinc-oxide (ZnO) thin-film transistors (TFTs), through TFT width scaling for gate resistance reduction. This f_{MAX} value is among the highest for metal-oxide TFTs with large-area and flex-compatibility. In terms of passive devices, flex-compatible large-area planar inductors are designed, fabricated, and characterized. A record-high quality factor of up to ~65 in 2.4-GHz Wi-Fi frequency band is demonstrated using those inductors, which is over 3 times that of prior state-of-art inductors with similar geometry, in a similar frequency band. The Princeton Materials Institute's cleanroom facilitates were used for device fabrication in this project.

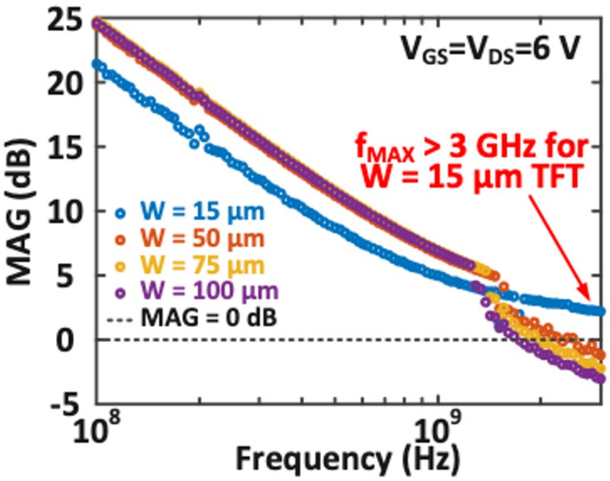


Figure 1. Measured maximum available power gain (MAG) of ZnO TFTs with channel length $L = \sim 1\ \mu m$ and various channel width W, at $V_{GS} = V_{DS} = 6\ V$. Unity power gain frequency f_{MAX} exceeding 3 GHz is observed in TFT with $W = 15\ \mu m$.

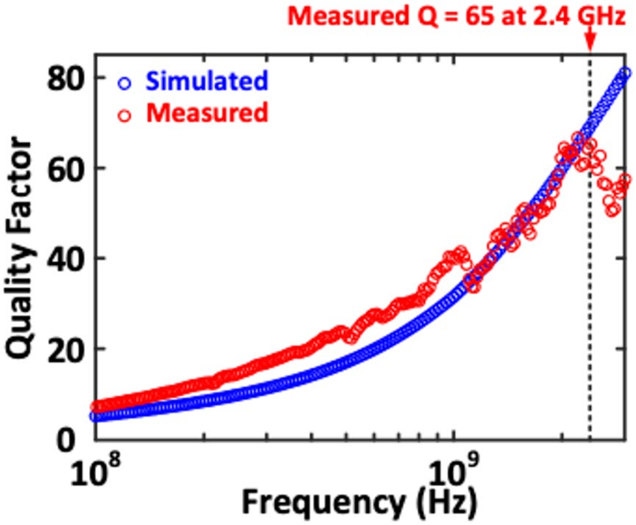


Figure 2. Comparison of quality factor between simulation and measurement. In experiment, the LAE-based flex-compatible planar inductor is made of 2.5-μm thick silver, with a radius of 1 mm and a trace with of 0.2 mm.

CITATIONS:

[1] Y. Ma, S. Wagner, N. Verma and J. C. Sturm, "f_{MAX} Exceeding 3 GHz in Self-Aligned Zinc-Oxide Thin-Film Transistors with Micron-Scale Gate Length," 2023 Device Research Conference (DRC), pp. 1-2. IEEE, 2023.
[2] Y. Ma, S. Wagner, N. Verma and J. C. Sturm, "High Quality-Factor Planar Inductors Compatible with Flexible Large-Area Electronics for Integrated IoT and 5G/6G Applications," 2023 IEEE International Flexible Electronics Technology Conference (IFETC), pp. 1-3. IEEE, 2023.

Advisor: James Sturm

Project Tittle: Oxygen Plasma Treatment for Top-Gate ZnO Thin-Film Transistors (TFTs)

Researcher: Zili Tang (Graduate)

Thin-film transistors (TFTs) are field-effect transistors with thin films as the active semiconductor layer. A common structure of the TFT is shown in Fig. 1(a). This structure provides various advantages such as simple fabrication procedure, high stability due to protection of the ZnO active region by an Al_2O_3 passivation layer, and potentially high frequency operation due to no overlap capacitance between the gate and the source/drain. However, a gap between S/D and G is required to due to photolithographic alignment tolerance. This gap can create a high series resistance (~150 kΩ for every 1 µm gap) compared to the resistance in the channel resistance (~1 kΩ for every 1 µm channel length), significantly limiting the output current and the cut-off frequency of the TFT. Images of the TFTs fabricated in the Micro/Nanofabrication Center (MNFC) are shown in Fig. 1(b), with a zoomed-in image (Fig. 1(c)) showing the gap between the gate and the source/drain of the TFT. To reduce the series resistance in the gap region of the TFTs, it is obligatory to reduce the sheet resistance of the ZnO layer. Oxygen plasma have been observed to reduce the resistivity of ZnO [1]. To examine the effect of the oxygen plasma on the sheet resistance of our ZnO sample, test structures shown in Fig. 2(a) have been fabricated to measure the sheet resistance of the ZnO with or without plasma treatment. By applying a voltage across the two outer metal contacts while measuring the voltage difference of the two middle metal contacts, the sheet resistance of the ZnO can be extracted. An image of the fabricated test structures is shown in Fig. 2(b). By fabricating arrays of the test structures across a wafer, a map showing the distribution of the ZnO sheet resistance can be created (Fig. 2(c)). By comparing the sheet resistance distribution under different plasma treatment conditions, it is possible to pinpoint the plasma condition most effective at reducing the sheet resistance of ZnO, and the regions on the wafer most sensitive to the plasma treatment.

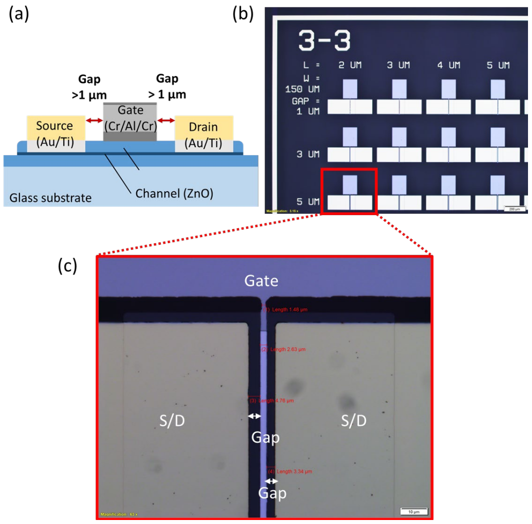
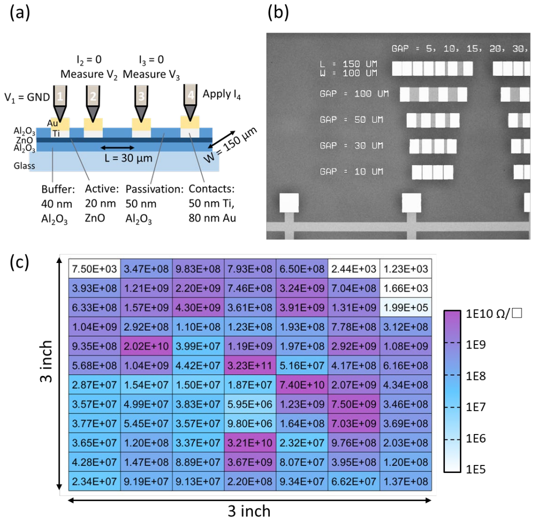


Figure 1: (a) cross-sectional illustration of a TFT; (b) top-view image of the TFTs; (c) zoomed-in top-view image of a TFT showing gaps between the gate and the source/drain.



7.50E+03	3.47E+08	9.83E+08	7.93E+08	6.50E+08	2.44E+03	1.23E+03
3.93E+08	1.21E+09	2.20E+09	7.46E+08	3.24E+09	7.04E+08	1.66E+03
6.33E+08	1.57E+09	4.30E+09	3.61E+08	3.91E+09	1.31E+09	1.99E+05
1.04E+09	2.92E+08	1.10E+08	1.23E+08	1.93E+08	7.78E+08	3.12E+08
9.35E+08	2.02E+10	3.99E+07	1.19E+09	1.97E+08	2.92E+09	1.08E+09
5.68E+08	1.04E+09	4.42E+07	3.23E+11	5.16E+07	4.17E+08	6.16E+08
2.87E+07	1.54E+07	1.50E+07	1.87E+07	7.40E+10	2.07E+09	4.34E+08
3.57E+07	4.99E+07	3.83E+07	5.95E+06	1.23E+09	7.50E+09	3.46E+08
3.77E+07	5.45E+07	3.57E+07	9.80E+06	1.64E+08	7.03E+09	3.69E+08
3.65E+07	1.20E+08	3.37E+07	3.21E+10	2.32E+07	9.76E+08	2.03E+08
4.28E+07	1.47E+08	8.89E+07	3.67E+09	8.07E+07	3.95E+08	1.20E+08
2.34E+07	9.19E+07	9.13E+07	2.20E+08	9.34E+07	6.62E+07	1.37E+08

Figure 2: (a) cross-sectional illustration of the test structure and the method for extracting the sheet resistance of the ZnO layer; (b) top-view image of the test structures; (c) sheet resistance of the ZnO layer across a 3-inch wafer.

CITATIONS: [1] A. A. Talukder et al, "Improving electrical properties of sol-gel derived zinc oxide thin films by plasma treatment," J. Appl. Phys., Oct. 2016

Advisor: Jeffrey D. Thompson
Project Tittle: Rare Earth Ion Qubits
Researcher: Cady Feng (Undergraduate)
Sponsorship: U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Co- design Center for Quantum Advantage

Rare earth ion impurity atoms in crystalline hosts feature electronic spin and optical transitions with long coherence times and the potential for strong interactions. Efficiently isolating and manipulating individual rare earth impurities is an outstanding challenge, however, since their optical transitions are typically E1-forbidden and therefore slow. Our research is aimed at circumventing this challenge by integrating single rare earth ions into nanophotonic optical structures that can enhance the emission rate by many orders of magnitude. One current area of interest is developing telecom-wavelength single photon sources and quantum memories for quantum repeaters based on single Erbium ions. Another is developing strongly interacting few-spin networks to study spin dynamics and applications to quantum information processing.

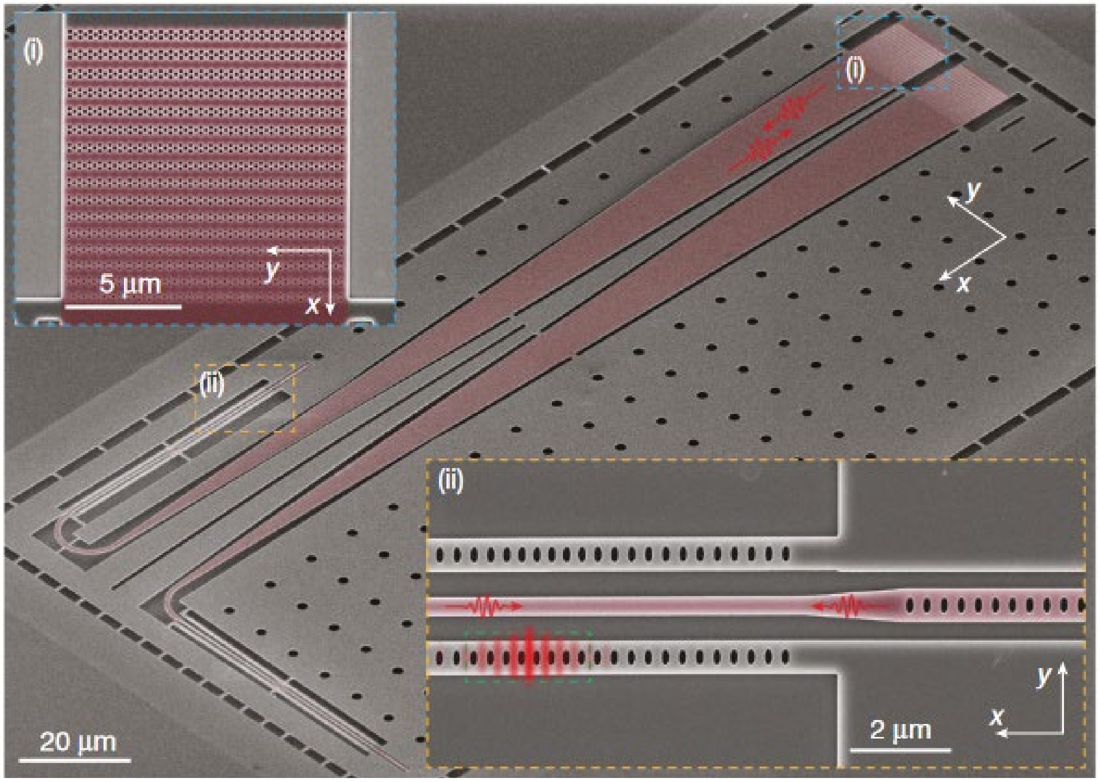


Figure 1: Er 3+: CaWO 4 device architecture. Scanning electron microscope image of a representative silicon nanophotonic device, consisting of a photonic crystal grating coupler (inset (i)) that tapers adiabatically into a bus waveguide connected to a photonic crystal nanobeam cavity (inset (ii)) [1]

CITATIONS:
S. Ourari, Ł.Dusanowski, S. P. Horvath, M. T. Uysal, Ch. M. Phenicie, P. Stevenson, M. Raha, S. Chen, R. J. Cava, N.P. de Leon & J. D. Thompson; *Indistinguishable telecom band photons from a single Er ion in the solid state;* Nature volume 620, pages 977–981 (2023)

Advisor: Saien Xie
Project Title: Substrate engineering for growth of two-dimensional materials
Researcher: Satya Butler (Graduate)
Sponsorship: Princeton University

Layered two-dimensional materials (2D materials) can be grown in very thin sheets, even down to monolayers that may be one or a few atoms thick. Individual 2D materials and 2D material heterostructures are increasingly being studied for future electronic and optoelectronic applications. While many properties are intrinsic to the materials themselves, distinct behavior can arise from the substrate underneath the 2D material. To further understand these materials and expand their functionality, this work studies the change in behavior of 2D materials on custom designed substrates that are fabricated in the MNFC.

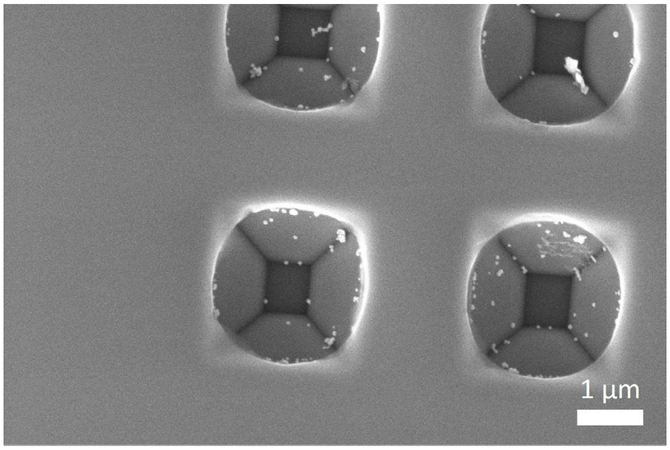


Figure 1: Inverted pyramids etched into a SiO_2/Si substrate.

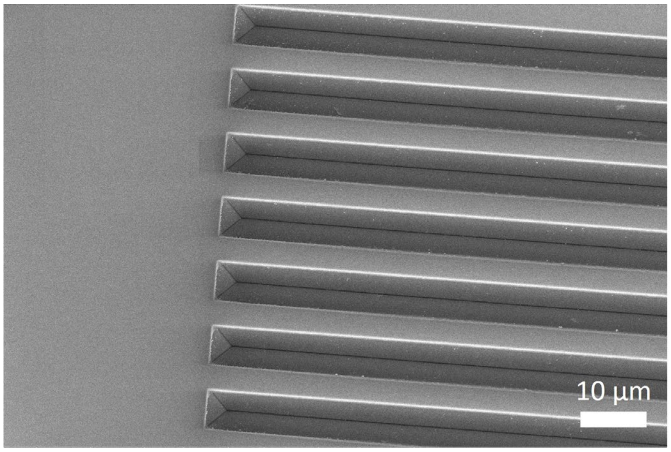


Figure 2: Inverted pyramidal trenches etched into a SiO2/Si substrate.

Advisor: Saien Xie

Project Tittle: Electronic Devices Based on 2D materials.

Researcher: Jinpeng Tian (Postdoc); Haining Mao (Graduate)

Sponsorship: Princeton University

We study 2D materials for future electronic and optoelectronic applications. First, we deposit monolayer WS2 on SiO2 substrate by MOCVD. Then, electrodes, gate, and dielectric layer are fabricated in MNFC by e-beam lithography, e-beam evaporator and ALD.

Figure 1: BN encapsulated WS2 devices

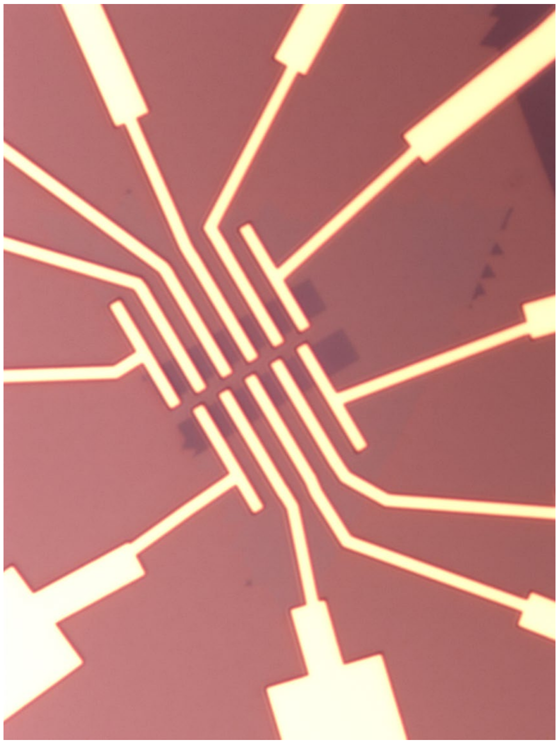


Figure 2: WSe2 field effect transistors on SiO2 substrate

Advisor: Mark A. Zondlo
Project Tittle: NitroNet
Researcher: Vladislav Sevostianov (Graduate)
Sponsorship: DOE

Nitrous oxide (N2O) is a potent greenhouse gas. With an atmospheric lifetime of 114 years, it is approximately 300 times more effective at heating the Earth's surface relative to CO2. Nitrogen management for agricultural production of crops, the primary source of N2O, contributes approximately 4% of all greenhouse gases from the United States annually. However, the quantification of these emissions, which are non-uniform in space and time, is a significant challenge at the field and farm scales. NitroNet is an autonomous sensing system designed to monitor N2O emissions over an entire growing season at high spatial and temporal resolutions. By casting a virtual net over an entire field, NitroNet will identify areas within a field that produce N2O and when these pulses are emitted to the atmosphere. The total nitrogen loss over a growing season through N2O emissions will be quantified to inform practices that minimize the environmental effects of agricultural crop production. A first of its kind system, NitroNet uses eye-safe laser beams, low-cost reflectors and highly sensitive detectors around the perimeter of a field to measure N2O concentrations at 1-acre resolution without impacting regular agricultural activities, such as tillage, planting, fertilization and harvest. This continuous, laser-based monitoring will be validated using a small unmanned aerial system and compared to conventional approaches. NitroNet is a leading-edge product that will revolutionize how environmental nitrogen loss is monitored and will inform the future development of sustainable agricultural practices in the United States.

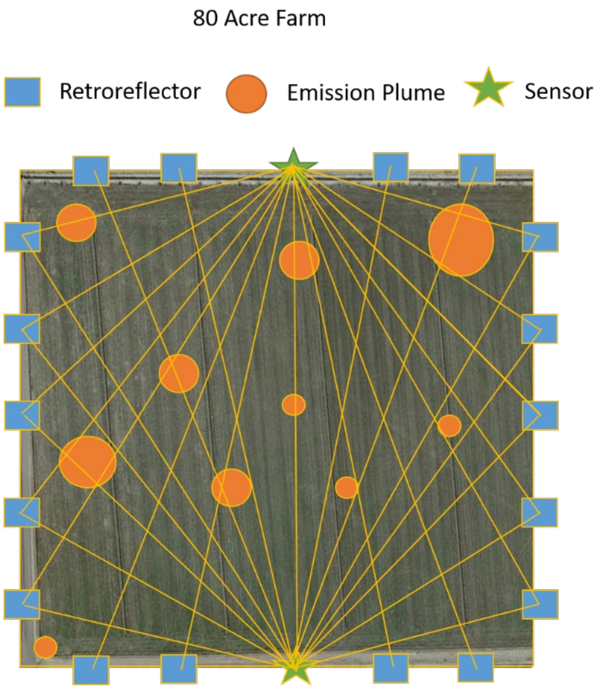


Figure 1: NitroNet schematic

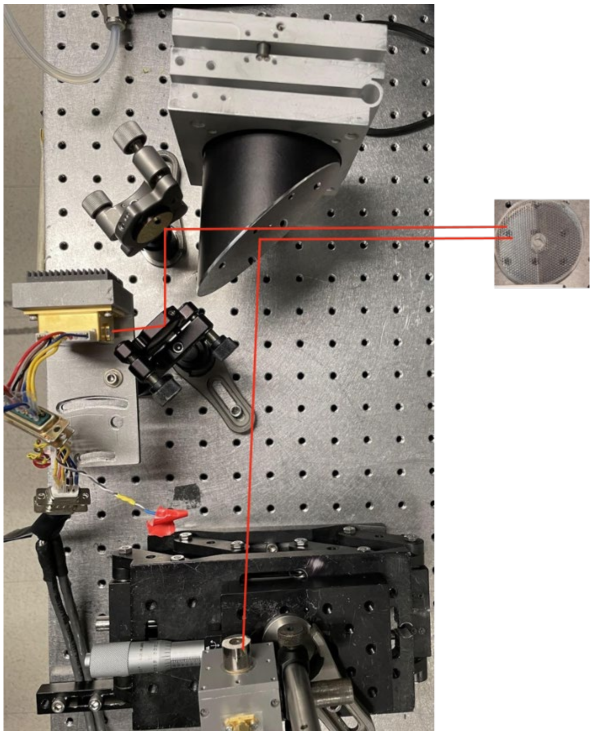


Figure 2: NitroNet optics

Mechanical and Aerospace Engineering

Advisor: Daniel J. Cohen

Project Tittle: Design and Fabrication of Electrodes for Electrotaxis

Researcher: Jeremy Yodh (Postdoc)

Sponsorship: Schmidt

We design and fabricate arrays of electrodes to generate spatiotemporal electric fields for guiding cell migration.

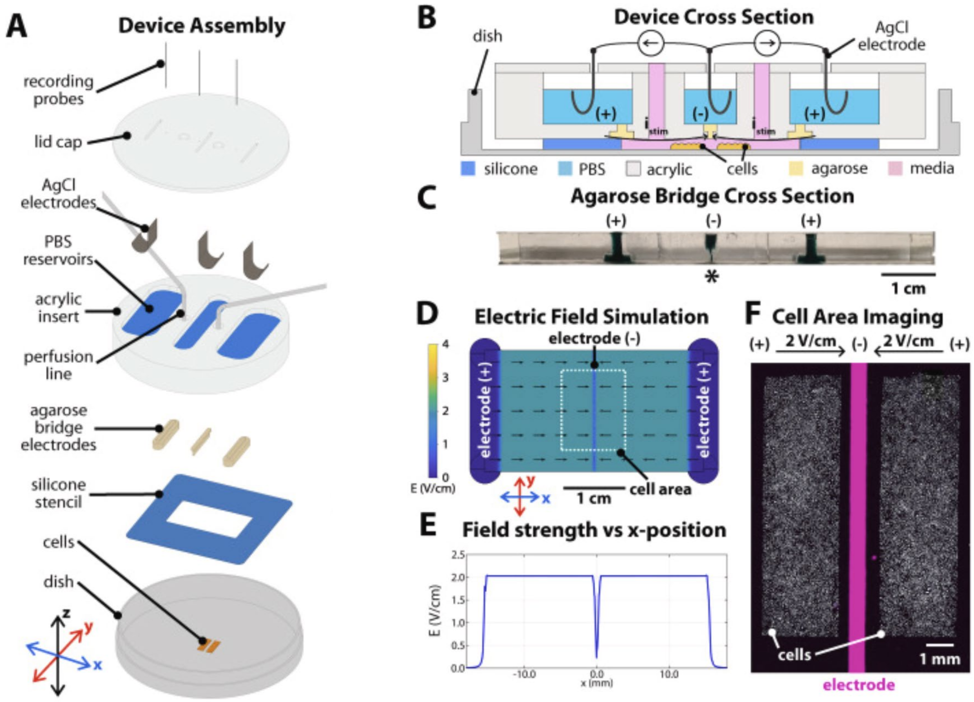


Figure 1. Convergent field stimulation device. (A) Layer-based assembly of the bioreactor onto a tissue culture dish. Cells are patterned in the center of the dish, then a 250 µm-thick silicone stencil is placed to define the stimulation area and height. Agarose bridges are cast inside an acrylic insert, then clamped into the dish and against the silicone stencil. The reservoirs on the topside of the acrylic insert are filled with phosphate-buffered saline (PBS). Chloridized silver electrodes and titanium wire recording probes are inserted in each reservoir, all held in place by a lid cap. (B) Device cross-section sketch and (C) photograph of the sectioned agarose bridges stained with green food coloring for contrast. The narrow cathode is labeled with '*'. (D) Numeric simulation of the electric field in the device, showing constant 2 V/cm field strength converging toward the center, with a steep drop-off in strength starting ±500 µm from the center. (E) Simulated field strength versus x-position in the device. (F) Microscope capture of the central area of the assembled device, showing the central electrode 500 µm wide positioned between the two tissues. The cells (white) were labeled with a Cy5 lipophilic dye and the outline of the central electrode was visualized with a DAPI filter set ($\lambda_{ex}/\lambda_{em}$ 358/461 nm) and filled via post-processing in ImageJ (magenta). [1]

CITATIONS:

[1] Tom J. Zajdel, Gawoon Shim, Daniel J. Cohen; Come together: On-chip bioelectric wound closure; Biosensors and Bioelectronics 192 (2021) 113479

Advisor: Howard A. Stone (Mechanical and Aerospace Engineering)

Project Tittle: Microtubule-Enabled Nanotechnology (MENT)

Researcher: Ryungeun Song (Princeton Postdoc)

Sponsorship: Princeton University - Eric and Wendy Schmidt Transformative Technology Fund

Microtubules (MTs) have essential functions within the cell, including providing a robust railroad for motor-driven cargo transport. The unique properties of MTs have stimulated attempts to harness these characteristics for targeted delivery of molecular complexes, novel material design, and developing nanotechnologies with precision comparable to living organisms. However, previous efforts mainly focused on MTs with fixed length and layout and no controlled MT generation, setting a limit on designing MT architecture. In this study, we integrated nanofabrication with MT branching reactions borrowed directly from the cell's toolkit to construct cytoskeletal circuits and generate MT architectures from scratch. That is, our system enables control over MT growth and autocatalytic nucleation on a microfluidic chip with micro/nanostructures patterned within.

Controllable platforms to engineer robust cytoskeletal scaffolds have the potential to create novel on-chip nanotechnologies. Inspired by axons, we combined the branching microtubule (MT) nucleation pathway with microfabrication to develop "cytoskeletal circuits." This active matter platform allows control over the adaptive self-organization of uniformly polarized MT arrays via geometric features of microstructures designed within a microfluidic confinement. We build and characterize basic elements, including turns and divisions, as well as complex regulatory elements, such as biased division and MT diodes, to construct various MT architectures on a chip. Our platform could be used in diverse applications, ranging from efficient on-chip molecular transport to mechanical nano-actuators. Further, cytoskeletal circuits can serve as a tool to study how the physical environment contributes to MT architecture in living cells.

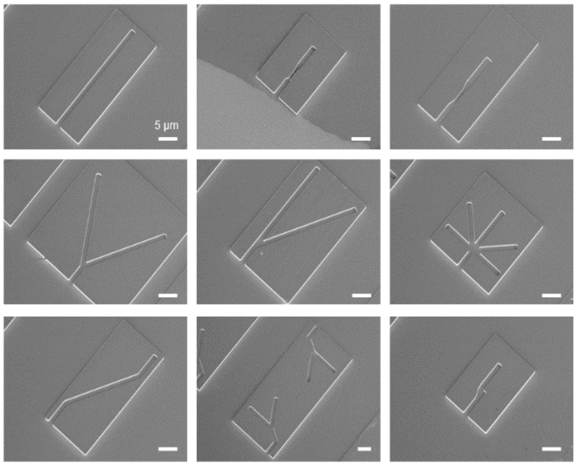


Figure 1. Scanning Electron Microscope (SEM) images that show the channel geometry to control the microtubule network on a microfluidic chip.

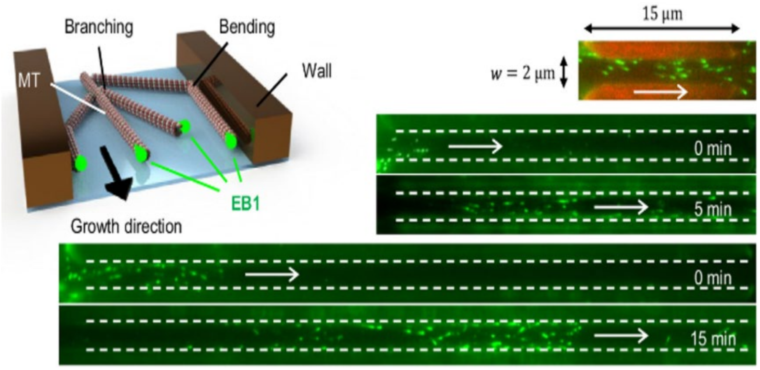


Figure 2. Schematics and experimental observations of branched MT networks self-organizing within straight channels with 15, 30, and 60 μm lengths. White arrows show the growth direction of microtubules.

CITATIONS:

Zaferani, M., Song, R., Petry, S. and Stone, H.A., 2024. Building on-chip cytoskeletal circuits via branched microtubule networks. Proceedings of the National Academy of Sciences, 121(4), p.e2315992121.

Physics

Advisor: Ali Yazdani

Project Tittle: STM Study on 2-Dimensional Materials

Researchers: Haotan Han (Graduate), Minhao He (Postdoc)

Sponsorship: ONR, MURI, ARO-MURI, NSF-DMR

The interaction between electrons in graphene under high magnetic fields drives the formation of a rich set of quantum Hall ferromagnetic (QHFM) phases with broken spin or valley symmetry. Visualizing atomic-scale electronic wave functions with scanning tunneling spectroscopy (STS), we resolved microscopic signatures of valley ordering in QHFM phases and spectral features of fractional quantum Hall phases of graphene. At charge neutrality, we observed a field-tuned continuous quantum phase transition from a valley-polarized state to an intervalley coherent state, with a Kekul distortion of its electronic density. Mapping the valley texture extracted from STS measurements of the Kekul phase, we could visualize valley skyrmion excitations localized near charged defects. Our techniques can be applied to examine valley-ordered phases and their topological excitations in a wide range of materials.

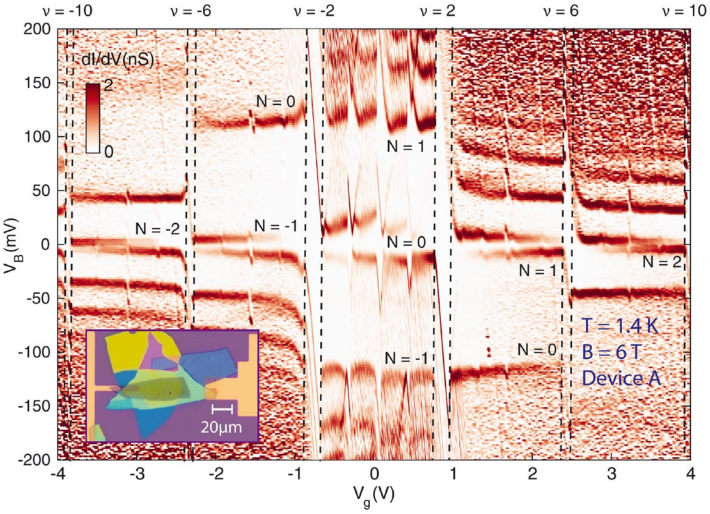


Figure 1: Tunneling spectra of device A as a function of bias voltage and gate voltage measured at *B* = 6 T, *T* = 1.4 K at a fixed tip height. Inset: Optical image of device A. The left gold pad contacts the graphite gate; the right contact connects with graphene. [1]

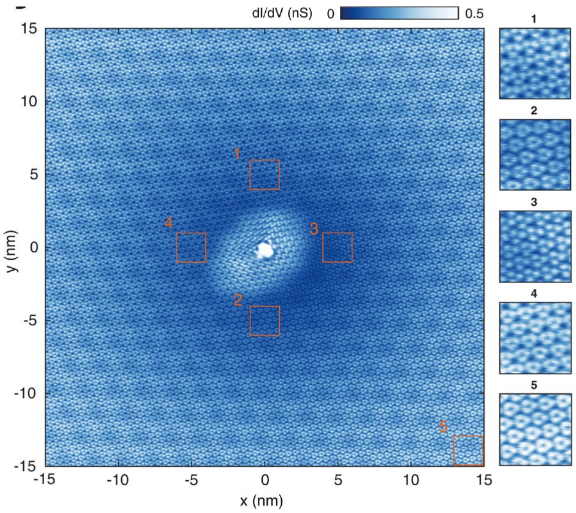


Figure 2: dI/dV map of the E-ZLL zoomed in the area near the point defect found on device. [1]

CITATIONS:

[1] Liu, X. et al. Visualizing broken symmetry and topological defects in a quantum Hall ferromagnet. Science 375, 321 326 (2022).

Advisor: Nai Phuan Ong

Project Tittle: Devices Using 2D Quantum Materials

Researcher: Xiao Yang (Graduate), Bingzheng Han (Graduate)

Sponsorship: Moore Foundation

We have studied edge supercurrents in superconducting topological materials, and we are looking forward to studying it in a thinner limit. The E-beam Lithography, plasma etching, and deposition are done in MNFC.

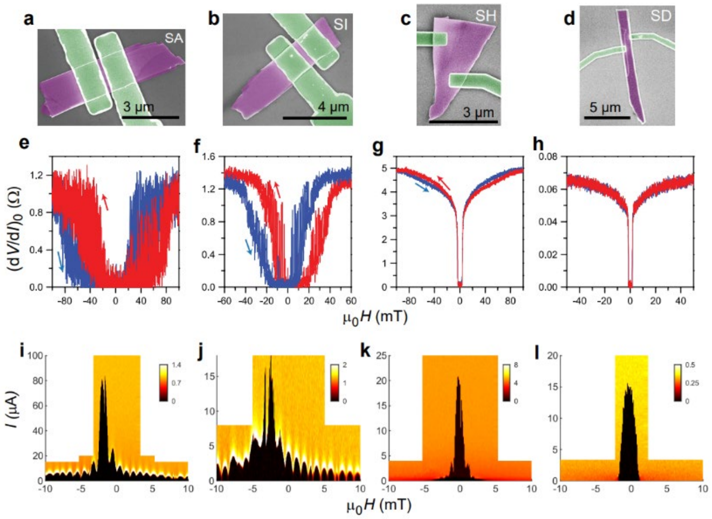


Figure 1: Systematic suppression of edge oscillations and anti-hysteresis in four devices (SA, SI, SH and SD in Panels a,...d, respectively). SA and SI (with spacing d = 156 and 285 nm, respectively) are examples from a series of 5 parallel-strip devices. SH and SD are from a second series in which the Nb contact volumes are decreased while ℓ1 and ℓ2 are progressively increased. The middle row (Panels e,...,h) shows the corresponding antihystereses in (dV /dI)o vs. H (blue and red arrows indicate field scan directions). The corresponding color maps of dV /dI vs. H and I are in the bottom row (i,..., l). In devices SA and SI, prominent antihysteresis and edge oscillations are seen, both in (dV /dI)o (Panels e, f) and their color maps (i, j). In devices SH and SD, these group II features are suppressed or absent in (dV /dI)o (Panels g and h) and in the color maps (k and l). See Table S1 for parameters in the 8 devices and Fig. S3 for results from devices SK, SJ, SB, SF .

Figure 2: An optical image of bottom gate and deposited electrodes for studying Nernst effect in a thinner limit.

CITATIONS:

Stephan Kim, Shiming Lei, Leslie M. Schoop, R. J. Cava, and N. P. Ong; *Eavesdropping on competing condensates by the edge supercurrent in a Weyl Superconductor*; https://doi.org/10.21203/rs.3.rs-2042169/v1

Advisor: Nai Phuan Ong

Project Tittle: Anyonic Edge Modes of 2D Quantum Materials

Researcher: Sangwoo Sim (Graduate), Nicholas Quirk (Graduate)

Sponsorship: Moore Foundation

The goal of this project is to make device out of graphene-hexagonal boron nitride heterostructures. My work is mainly done at Raith EBPG and Oxford RIE for the high-resolution patterning and etching process. Monolayer graphene exhibits a integer/fractional Quantum Hall effect at low temperature and high perpendicular magnetic field. In this regime, the current is only carried by the edge dissipationless channel, where the bulk remains insulating. Through additional quantum point contact, we are able to induce a tunneling process between the edge channels to precisely tune the transmission rate, or the number of channels that are backscattered.

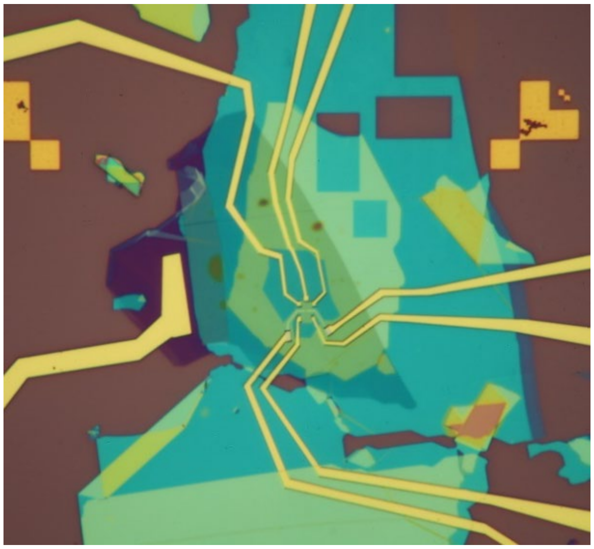


Figure 1 : Monolayer graphene encapsulated between hexagonal Boron Nitride, is cut into shape with reactive ion etching. Chrome/palladium/gold contacts (yellow) are added along with the palladium top gate (grey). The top split gate has a 25nm gap between its two triangular arms to form a quantum point contact.

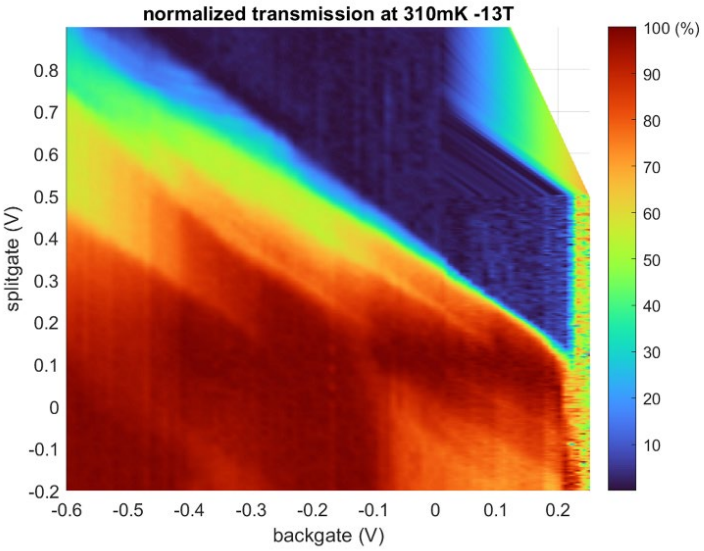


Figure 2 : Top split gate and back gate controlled transmission map in a graphene quantum point contact device. At low temperature (310mK) and a high perpendicular magnetic field (-13T), the dissipationless edge channels in graphene induced by the quantum Hall effect undergoes a quantized transmission rate by controlling the top split gate quantum point contact (saw-tooth profile).

Advisor: Sanfeng Wu

Project Tittle: Novel Quantum Devices Based on 2D Materials

Researcher: Haosen Guan (Graduate)

Sponsorship: AFOSR

We are developing nanoscale devices with 2D materials to study topological quantum effects. We use e-beam lithography, e-beam metal deposition, and reactive ion etching to pattern the metal contacts and on Si wafers.

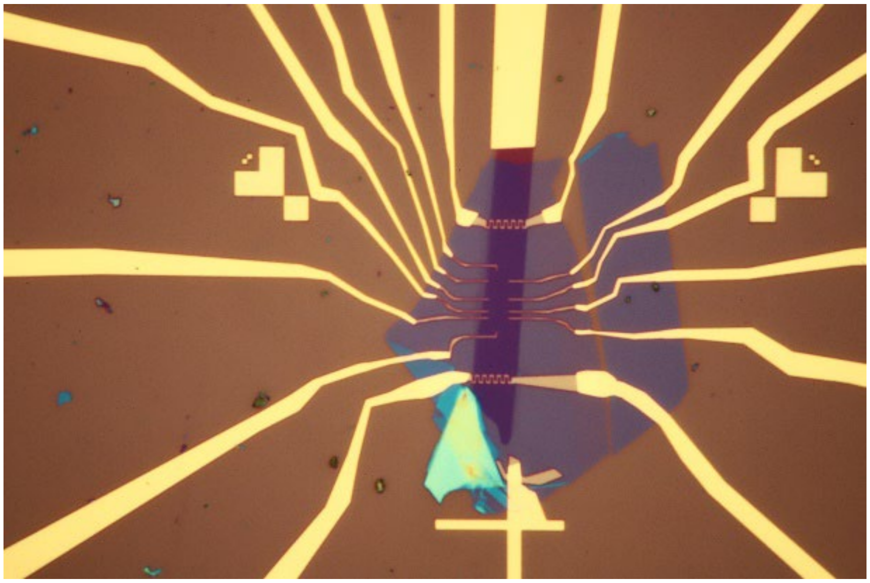


Figure 1: Metal contacts with 2D materials

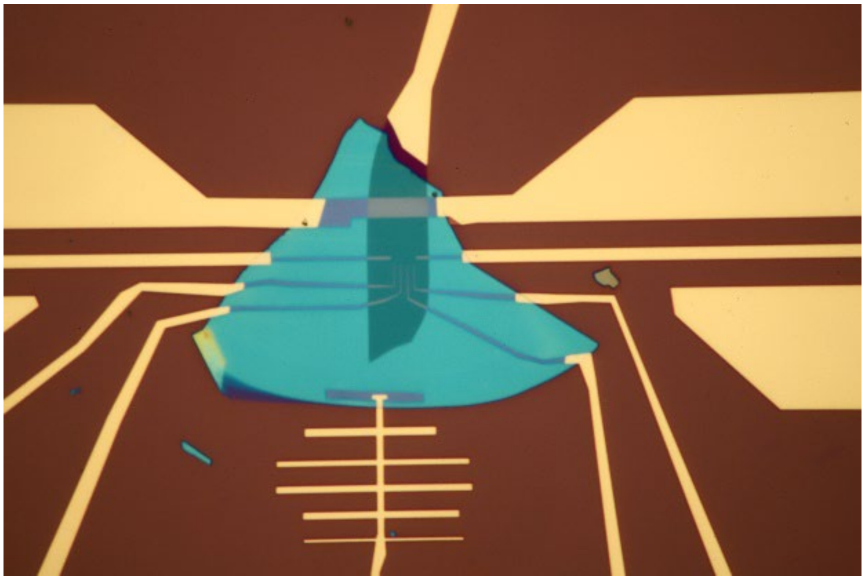


Figure 2: Wave guide and metal contacts with 2D materials

Advisor: Sanfeng Wu
Project Tittle: Surface-confined two-dimensional mass transport and crystal growth on monolayer materials
Researcher: Yanyu Jia (Graduate)
Sponsorship: ONR YIP

Rapid, long-distance transport of an ultrathin and uniform palladium film on a two-dimensional (2D) crystal of tungsten ditelluride at accessible temperatures is reported. The surprising effect is generalizable and offers possibilities for exploring chemical synthesis in nanoconfined spaces and access to not yet synthesized 2D materials. The fabrication of such vdW stacks were mainly performed in MNFC, which requires multiple tools such as EBPG, and Eline e-beam writers, RIE, Dual Chamber electron beam evaporator, etc.

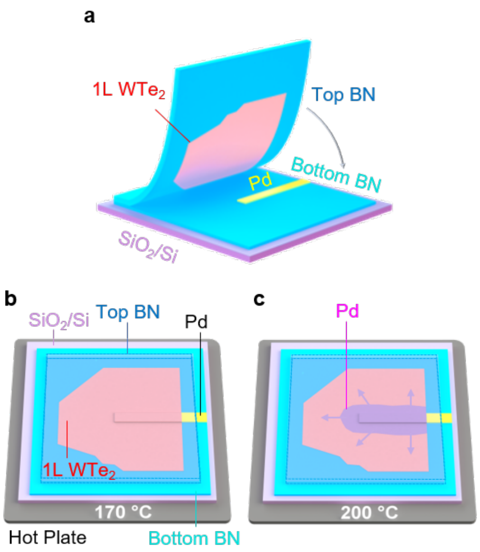


Figure 1: a, Illustration showing the preparation of the stack comprising a metal seed (Pd) and a 2D crystal (WTe2 monolayer), fully encapsulated by hexagonal boron nitride (hBN), on a SiO2/Si substrate. b, The final stack was heated to ~170 °C, and showed no reactions. c, Upon heating to ~200 °C, rapid, long-distance, non-Fickian transport of a 2D ultrathin Pd film was observed.

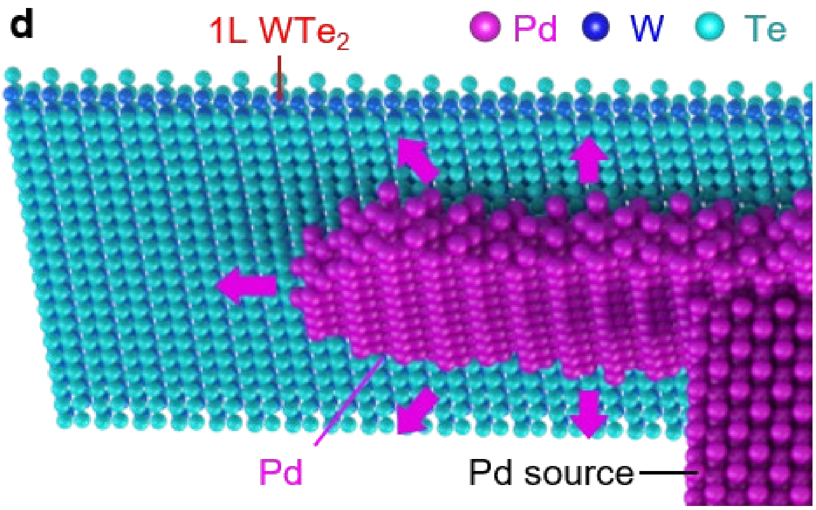


Figure 2: d, Cartoon illustration of the mass transport, which results in the synthesis of a 2D crystalline compound, Pd7WTe2. 1L, monolayer.

Advisor: Sanfeng Wu

Project Tittle: Topological Quantum Phases in 2D Materials

Researcher: Mike Onyszczak

Sponsorship: ONR, NSF, Moore Foundation

This project aims to fabricate quantum devices based on 2D materials, such as graphene, boron nitride, and transition metal dichalcogenides, for quantum transport measurements as well far infrared spectroscopy. We study the interplay between the topological phases and novel superconducting states in these materials. Nanofabrication of electrodes, metal gates, and heaters was performed in the MNFC.

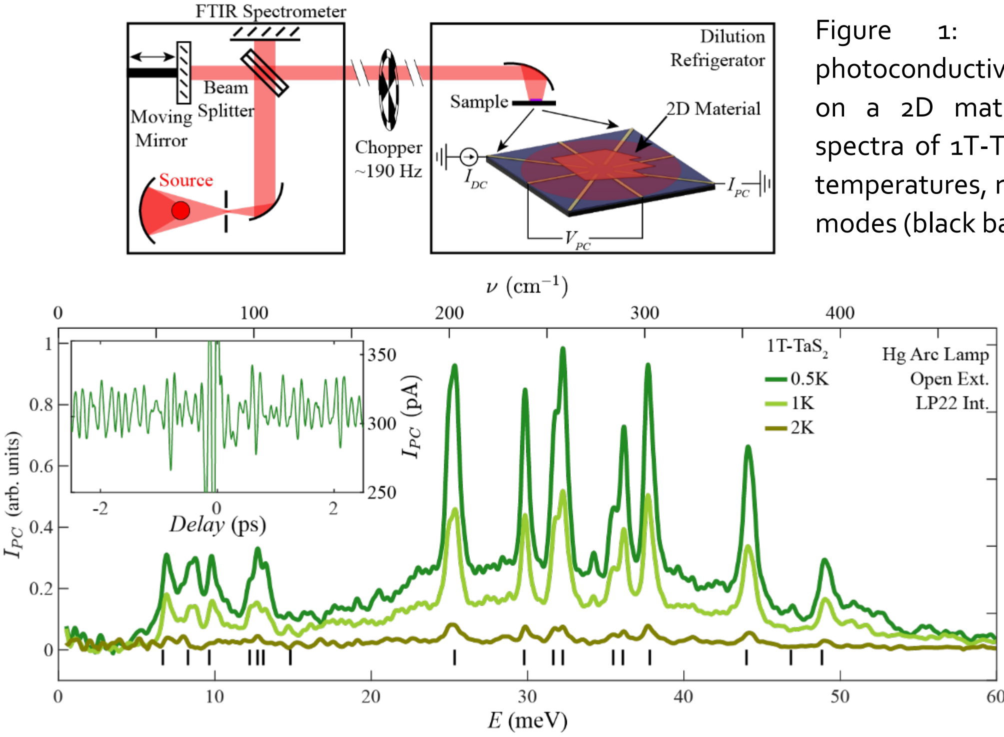
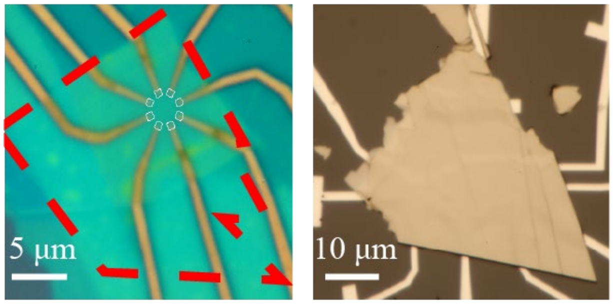


Figure 1: Top: A schematic of photoconductivity based FTIR measurements on a 2D material. Bottom: Photocurrent spectra of 1T-TaS2, taken at three different temperatures, revealing the IR active phonon modes (black bars) of 1T-TaS2



Monolayer WTe$_2$ 1T-TaS$_2$

Figure 2: Optical Image of monolayer WTe$_2$ (outlined in red) and many layered 1T-TaS$_2$ Nanodevices used in photocurrent spectroscopy measurements.

CITATIONS:

M. Onyszczak, A.J. Uzan-Narovlansky, Y. Tang, P. Wang, Y. Jia, G. Yu, T. Song, R. Singha, J.F. Khoury, L.M. Schoop, and S. Wu, "A platform for far-infrared spectroscopy of quantum materials at millikelvin temperatures," Review of Scientific Instruments 94(10), 103903 (2023).

Advisor: Sanfeng Wu
Project Tittle: Topological Quantum Devices
Researcher: Zhaoyi Joy Zheng
Sponsorship: ONR

We are developing nanoscale devices with 2D materials to study topological quantum effects. We use e-beam lithography, e-beam metal deposition, and reactive ion etching to pattern the metal contacts and on Si wafers.

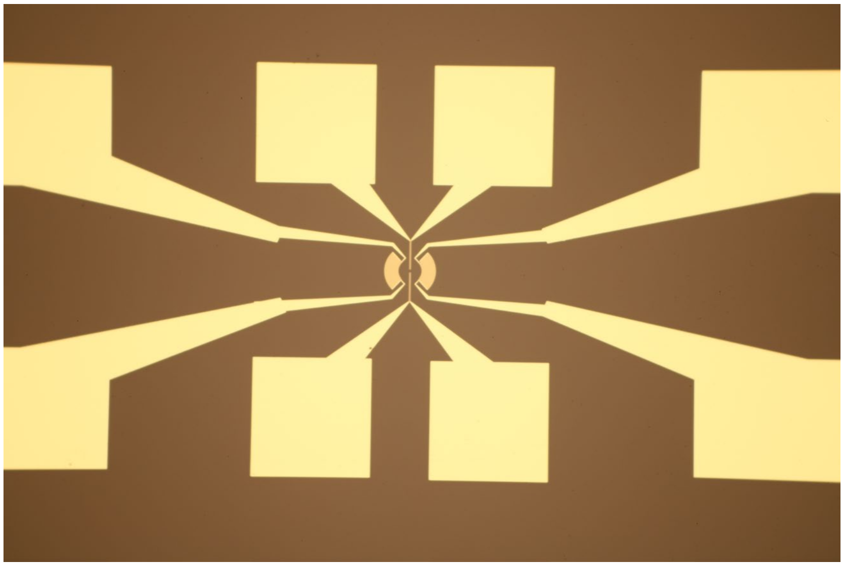


Figure 1: Surface acoustic resonator using Ti/Au metal.

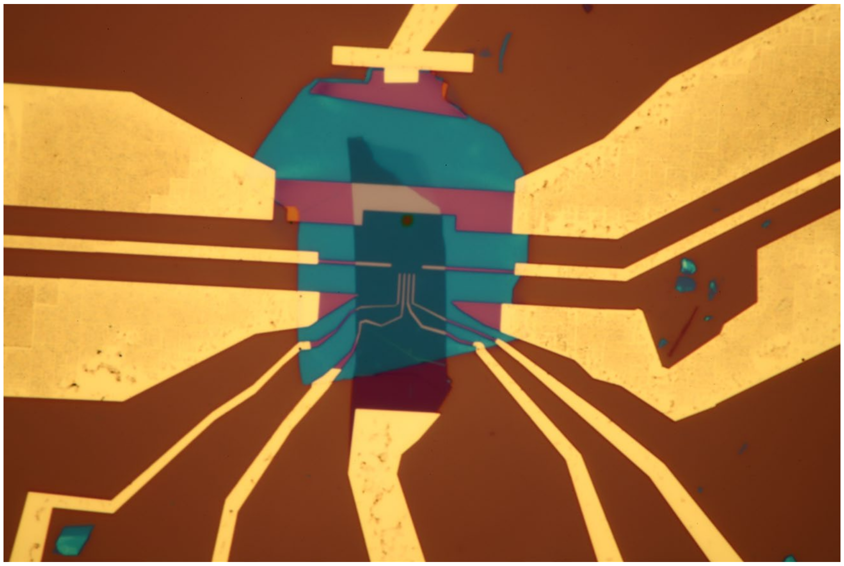


Figure 2: Ti/Au gate contacts with 2D TMD materials.

Advisor: Ali Yazdani (Physics)

Project Title: Multifunctional devices (van der Waals)

Researcher: Ryan Lee (Graduate),Jungwoo Lee (Graduate)

We are interested in studying electronic properties of graphene-based 2D van der Waals heterostructures using scanning tunneling microscopy (STM). Under high-magnetic fields, strong electronic interactions lead to emergent electronic phases including quantum Hall ferromagnets, fractional quantum Hall states, Wigner crystals, and exciton condensates. However, such electronic phases are known to be fragile and even a small perturbation from the STM tip could annihilate them. We are designing and developing a new type of device that allows us to resolve the fragile phases by minimizing these perturbations. From this new type of design, we expect to image these fragile quantum phases. In the MNFC clean room, we fabricated gold-patterned silicon chips as a component of our devices.

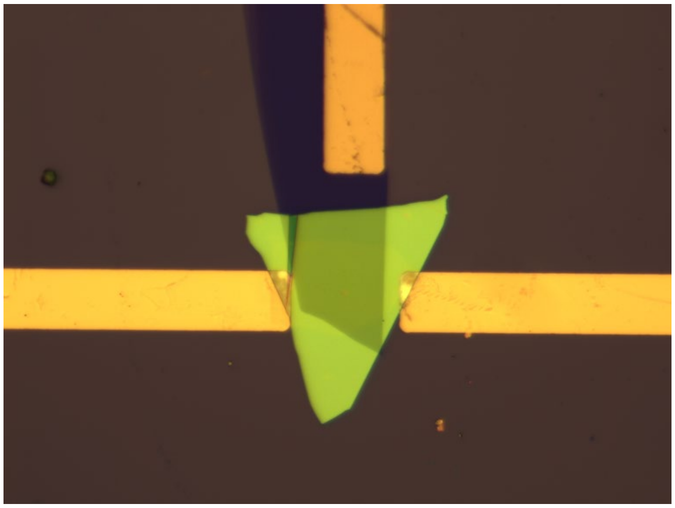


Figure 1: Optical image of our new design device.

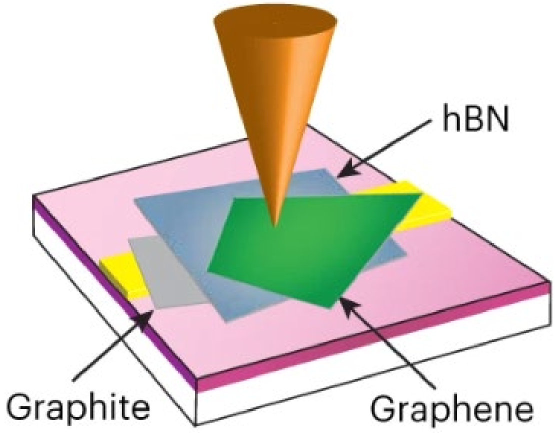


Figure 2. Device architecture [1]

CITATIONS:

[1] : Farahi, G., Chiu, CL., Liu, X. et al. Broken symmetries and excitation spectra of interacting electrons in partially filled Landau levels. Nat. Phys. 19, 1482–1488 (2023).

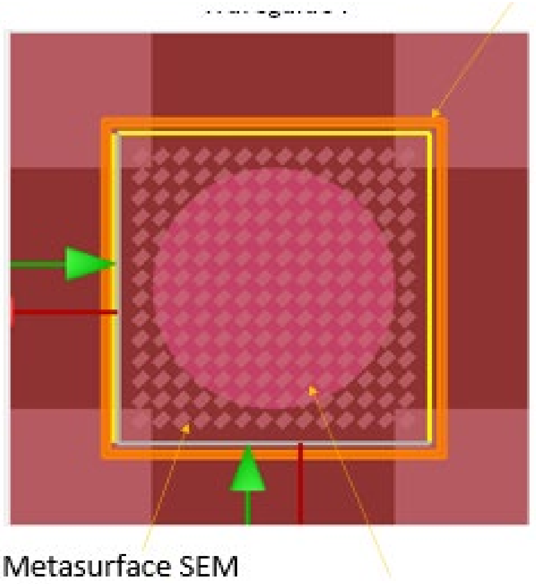
External Academic and Industrial

Company**:** Princeton Innotech Inc.

Project Tittle: Metasurface fabrication on surface emitting lasers

Researchers: Michel Francois, Frederick Won, Joshua Epstein, Peng Gao, George Zhang, Bingyu Zheng

Princeton Innotech is developing surface emitting lasers with meta-surfaces on top of them to achieve certain attributes for some special applications. The devices are fabricated using processes and equipment such as EBL (electron beam lithography), ICP, RIE, photolithography, electron beam evaporation systems, ALD (atomic layer deposition), as well as measurement tools such as SEMs, ellipsometer, and other characterization tools.



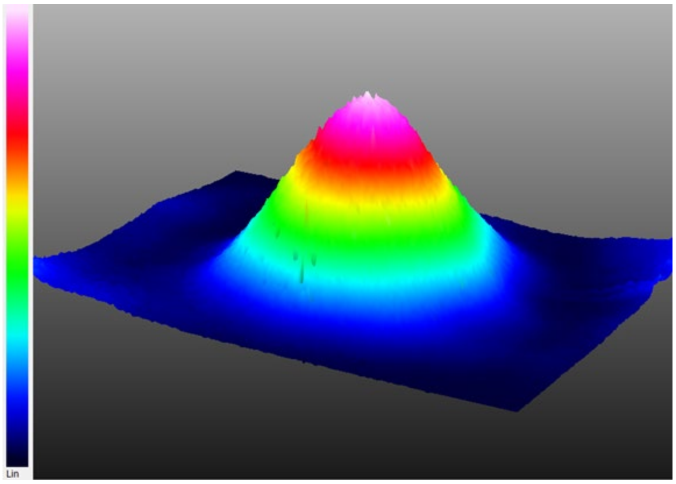


Figure 1: Picture of single mode beam profile from the surface emitting laser

Projects are funded by US-DoD through SBIR contracts.

Company: Princeton Infrared Technologies, Inc. (PIRT)

Project Tittle: Process Development - ALD Selective Etching on Type 2 Superlattice Detectors

Researchers: Matt Peart, Catherine Masie

Depositing Al_2O_3 ALD layer on InGaAs surface to provide better passivation for rougher epitaxial surfaces where silicon nitride was not as effective. ALD layer was etched away to form a patterned surface, etching method need to have high surface selectivity. A diode pattern is formed on the ALD deposited surface of the wafer, several etching methods were tested.

1. BOE wet etching: 30:1 prediluted with surfactant, NH_4F buffer was used, etching rate is around 0.4 nm/s, surface selectivity is good.
2. Dry etching: BCl3, Cl2 and Argon plasma etch was done here. The surface selectivity was good. Etching rate is around 0.7 nm/s
3. Other etching method was also tested. Such as Potassium Hydroxide, the surface selectivity is poor, the etchant strip off photoresist quickly.

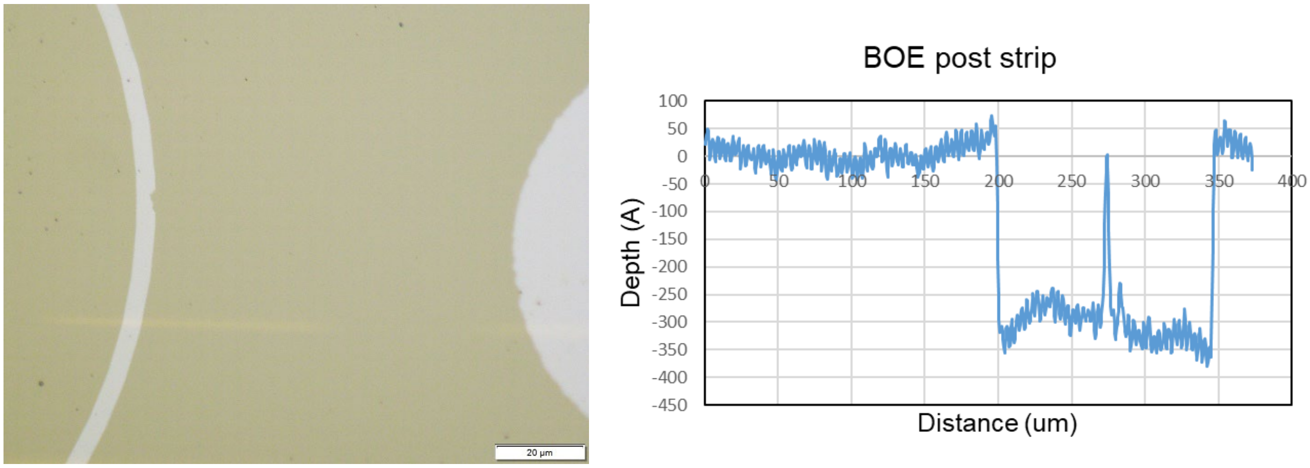


Figure 1: Al2O3 etched in BOE.

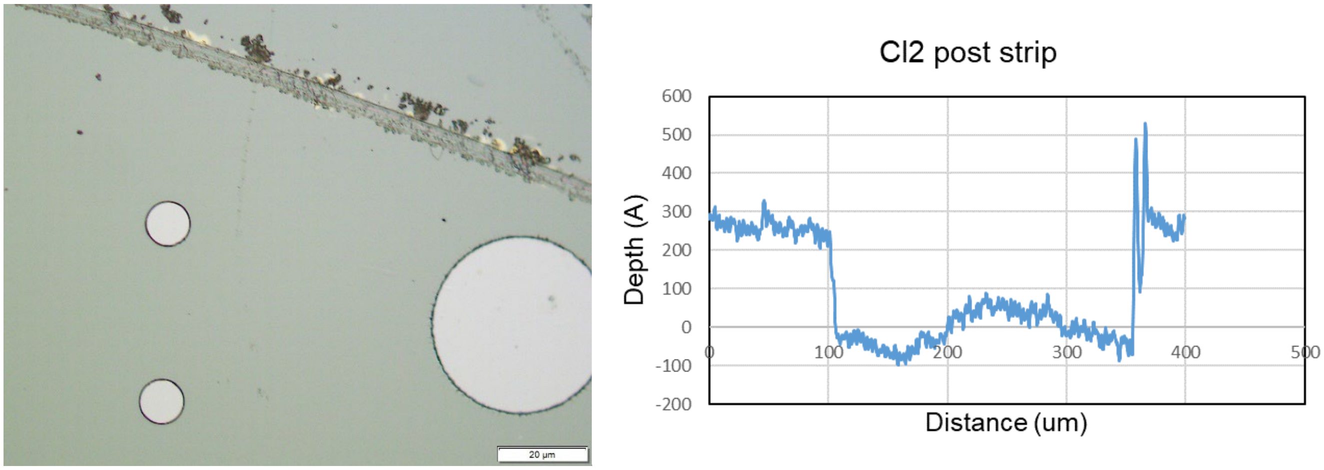


Figure 2 Results of chlorine plasma dry etching of Al2O3.

Company: SNOChip Inc.
Project Tittle: Nanostructures on Photonic Chips
Researcher: Wei Ting Chen

SNOChip focuses on developing metasurface components [1, 2] for the next generation imaging and sensing applications. Metasurface is composed of nanostructures spaced at sub-wavelength intervals, which are capable of controlling the phase delay of incident light. By manipulating the shape and arrangement of these nanostructures, we can replicate the functions of traditional optical elements—such as lenses, waveplates, and polarizers—using just a thin layer of nanostructures [3, 4]. Here at MNFC, we have developed specialized fabrication recipes for prototyping metasurfaces. As illustrated in the accompanying figure, our techniques enable the fabrication of high-aspect-ratio nanostructures on various substrates. At the time of preparing this report, we have successfully developed fabrication recipes for both amorphous silicon (aSi) nanopillars and silicon nitride (SiN) nanopillars, each tailored for specific applications across the visible and infrared spectra. Building on these advancements, we are poised to advance optical technology, paving the way for innovative applications and breakthroughs in fields ranging from high-resolution imaging to advanced sensing systems.

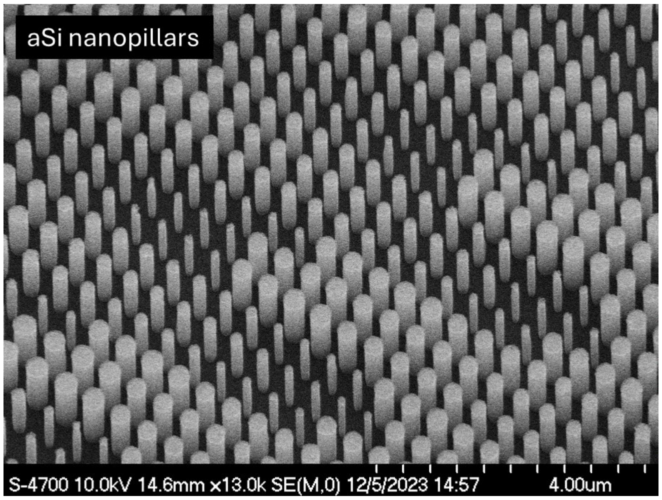


Figure 1: High-aspect-ratio aSi nanopillars on a glass substrate fabricated at MNFC.

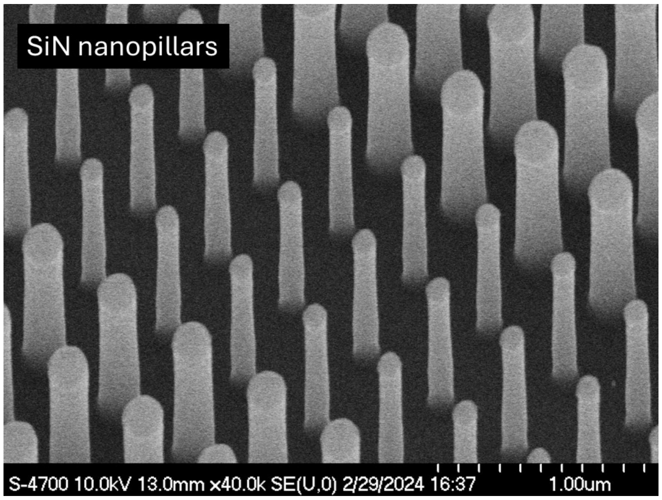


Figure 2: High-aspect-ratio SiN nanopillars on a glass substrate fabricated at MNFC.

CITATIONS:

[1] W. T. Chen, A. Y. Zhu, V. Sanjeev, M. Khorasaninejad, Z. Shi, E. Lee, and F. Capasso, "A broadband achromatic metalens for focusing and imaging in the visible," *Nat. Nanotechnol.* 13, 220-226 (2018).

[2] M. Khorasaninejad, W. T. Chen, R. C. Devlin, J. Oh, A. Y. Zhu, and F. Capasso, "Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging," *Science* 352, 1190-1194 (2016).

[3] W. T. Chen and F. Capasso, "Will flat optics appear in everyday life anytime soon?," *Appl. Phys. Lett.* 118, 100503 (2021).

[4] W. T. Chen, A. Y. Zhu, and F. Capasso, "Flat optics with dispersion-engineered metasurfaces," *Nat. Rev. Mater* 5, 604-620 (2020).

Company: Tendo Technologies, Inc.

Project Tittle: Development of a Low-Volume Flow Sensor

Researcher: Andojo Ongkodjojo Ong, Mark McMurray, Yuyang Fan, and Marcus Hultmark

Sponsorship: NSF – Small Business Innovation Research (NSF - SBIR) Phase I & II

Tendo Technologies, Inc. is developing a highly sensitive and accurate flow sensing mechanism, particularly suited for small volume fluids dispensing with our novel solid state flow sensors. This sensing mechanism utilizes electrically-conductive elastic filaments (*i.e.* a piezo-resistance). The passing flow will deflect the free-standing sensing elements, and then induce an axial strain within the material, resulting in a resistance change that is directly proportional to the flow. The polysilicon flow sensor can detect DPG (dipropylene glycol) flow at approximately 0.1 mL/min, that offers at least 70X higher sensitivity to low flows, when compared with the Platinum flow sensor. We develop the tiny flow sensors with the two temperature sensors based on the Platinum material (the original Elastic Filament Velocity (EFV)'s material) as shown in Fig. 1. These temperature sensors are simultaneously used to compensate for temperature and provide additional sensing capability readouts. The improvised flow sensors based on the polysilicon materials (Fig. 2) were then fabricated for increasing the Gauge Factor (GF) and reducing the Temperature Coefficients of Resistance (TCR). The three temperature sensors (the cold-wire sensors as shown in Fig. 2(a)), and the TDS (Total Dissolved Solids) sensors as shown in Fig. 2(b) are integrated onto the single sensor chip for expanding the sensing capabilities. For protection and application in the fields, the whole sensor chips were coated by the parylene-C as a barrier coating (Fig. 2(c)). The better properties of the fabricated polysilicon-based tiny flow sensors directly meet the needs of customers in several segments of industry from pharmaceutical dispensing, scientific R&D, and manufacturing.

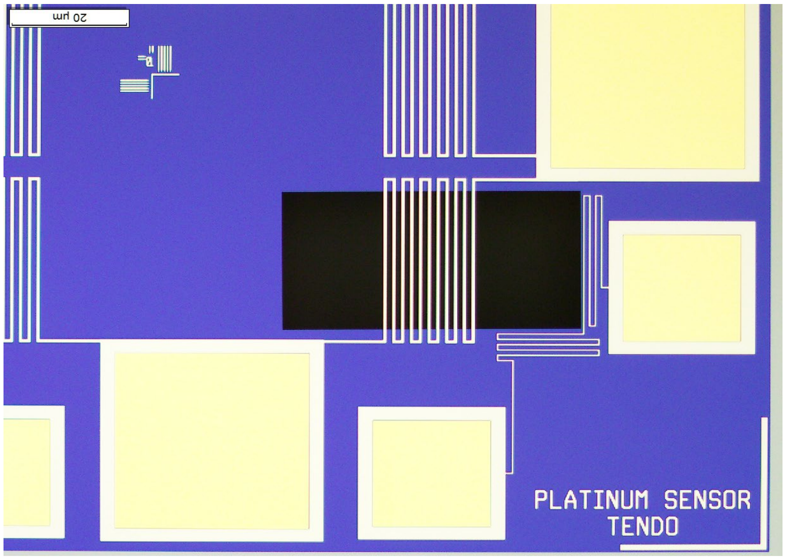


Figure 1: The platinum (Pt)-based flow sensor (Elastic Filament Velocity) with the eleven sensing wires is suspended over the silicon substrate, having a beam length of ~500 µm, a beam width of ~10 µm, and a thickness of ~100 nm. The two temperature sensors are integrated onto the same chip. The left one is not shown for the clarity of the free-standing sensing wires, close to the temperature sensor in the right corner site.

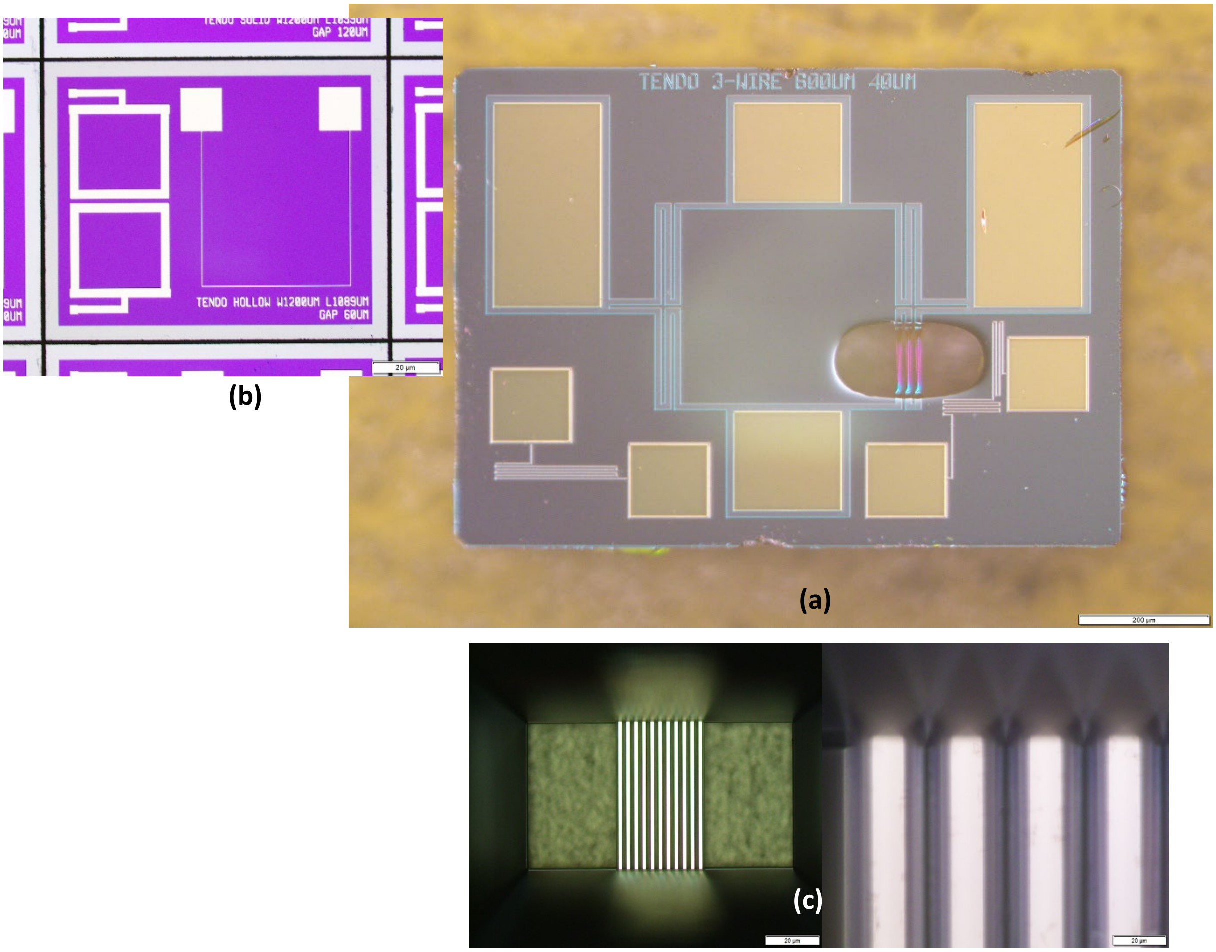


Figure 2: (a) The polysilicon-based flow sensor with the three sensing wires is suspended over the silicon substrate, having a beam length of ~500 µm, a beam width of 40 µm, and a thickness of ~100 nm. The two temperature sensors are integrated onto the same chip as shown on the frontside of the sensor chip. The temperature sensor is located on the backside is not shown. (b) The TDS (Total Dissolved Solids) sensors were also fabricated. They will be re-designed and integrated onto a single chip. (c) The sensing wires were coated by the parylene-C from the backside of the sensor chip with a high magnification of 100X as shown in the right side of Fig. 2(c).

CITATIONS:

M. K. Fu, Y. Fan, C. P. Byers, T.-H. Chen and C. B. Arnold, and M. Hultmark, "Elastic Filament Velocimetry (EFV)", Measurement Science and Technology, 2017, Vol. 28, 025301 (12pp).

"Marcus Hultmark, Clayton Byers, Matthew Fu, and Yuyang Fan. Elastic Filament Velocity Sensor. In: USPTO, ed.2020.

Other Research Examples Performed in the MNFC

Advisor: Sujit S. Datta (Chemical and Biological Engineering)
Project Title: Morphodynamics of Bacterial Communities in Polymeric Environments
Researcher: Sebastian Gonzalez La Corte (Graduate)
Sponsorship: NSF

Advisor: Jyotirmoy Mandal (Civil and Environmental Engineering)
Project Title: Micro Patterned Emitters for Control of Spectrum Direction of Thermal Radiation
Researcher: Mathis Degeorges (Visiting Researcher)
Sponsorship: Faculty Startup Funds

Advisor: Nathalie P. de Leon (Electrical and Computer Engineering)
Project Title: Diamond Quantum Devices
Researchers: Alexander Abulnaga (Graduate), Sean Karg Graduate), Alexander Pakpour-Tabrizi (Postdoc), Zeeshawn Kazi (Postdoc) Lila Rodgers (Graduate), Yuan, Zhiyang (Graduate), Marjana Mahdia (Graduate), Kai-Hung Cheng (Graduate), Jared Rovny (Postdoc)

Advisor: Nathalie P. de Leon (Electrical and Computer Engineering)
Project Title: Superconducting Qubits
Researchers: Ray Chang (Graduate), Apoorv Jindal (Postdoc), Basha Waxman (Undergraduate), Russell McLellan (Graduate), Nana Shumiya (Postdoc), Maxwell Lin (Undergraduate), Esha Umbarkar (Undergraduate)

Advisor: Advisor: Tian-Ming Fu (Electrical and Computer Engineering)
Project Tittle: Nanoelectronics for Tissues
Researcher: Sara Kacmoli (Postdoc), Stanley Kong (Undergraduate), Elana Sverdlik (Undergraduate), Christopher Warren (Undergraduate), Sophie Yangyi (Undergraduate)

Advisor: Claire F. Gmachl (Electrical and Computer Engineering)
Project Tittle: Quantum Cascade Lasers
Researchers: Radhika Bhuckory (Graduate), Richard Brun (Graduate), Danxian Liu (Undergraduate), Abigail McRea (Undergraduate), Rosy Monaghan (Undergraduate)

Advisor: Andrew Houck (Electrical and Computer Engineering)
Project Title: Qubits for Quantum Device Applications
Researchers: Matthew Bland (Graduate), Kevin Crowley (Graduate), Jacob Bryon (Graduate), Jeremiah Coleman (Graduate), Lev Krayzman (Postdoc), Shashwat Kumar (Graduate), Henry Prestegaard (Graduate), Sara Sussman (Graduate)

Advisor: Stephen A. Lyon (Electrical and Computer Engineering)
Project Title: Electrons on Helium
Researchers: Mayer Feldman (Graduate), Gordian Fuchs (Graduate), Emil Joseph (Postdoc), Matt Schulz (Graduate), Tiffany Liu (Graduate), Joe Radel (Undergraduate)

Advisor: Paul Prucnal (Electrical and Computer Engineering)
Project Title: Photonic Neuron
Researchers: Simon Bilodeau (Graduate), Eric Blow (Graduate), Weipeng Zhang (Graduate)

Advisor: Barry Rand (Electrical and Computer Engineering)
Project Title: Perovskite LEDs and Lasers
Researcher: James Loy (Graduate), Kwangdong Roh (Visiting Researcher)

Advisor: Kaushik Sengupta (Electrical and Computer Engineering)
Project Title: Terahertz, mmWave Circuit Designs
Researcher: Sherif Ghozzy (Graduate), Emir Ali Karahan (Graduate)

Advisor: Mansour Shayegan (Electrical and Computer Engineering)
Project Title: 2D Electron System
Researcher: Siddharth Kumar Singh (Graduate), Chia-Tse Tai (Graduate), Pranav Thekke Madathil (Graduate), Chengyu Wang (Graduate)

Advisor: James Sturm (Electrical and Computer Engineering)
Project Tittle: Microfluidic Cell Processing Device
Researcher: David Bershadsky (Undergraduate), Abiola Bolaji (Undergraduate), Kumar Mritunjay (Graduate), Miftahul Jannat Rasna (Graduate)

Advisor: Jeffrey D. Thompson (Electrical and Computer Engineering)
Project Tittle: Coherent Control of Solid-State Spins
Researchers: Joseph Alexander (Postdoc), Lukasz Dusanowski (Postdoc), Sebastian Horvath (Postdoc), Salim Ourari (Graduate), Sharon Platt (Graduate), Mehmet Tuna Uysal (Graduate)

Advisor: Saien Xie (Electrical and Computer Engineering)
Project Tittle: Light-switchable Logic Devices from Atomically-thin Organic-Inorganic Hybrid Junctions Spins
Researcher: Ji Jaehoon (Graduate)

Advisor: Daniel J. Cohen (Mechanical and Aerospace Engineering)
Project Tittle: 3D Nano-printing of Complex Materials
Researcher: Anamika (Postdoc), Lauren Rawson (Undergraduate), Durrah A. Ridhuan (Undergraduate)

Advisor: Marcus Hultmark (Mechanical and Aerospace Engineering)
Project Tittle: Turbulent Shear Stress Sensor
Researcher: Victoria Malarczyk (Graduate)

Advisor: Daniel R. Marlow (Physics)
Project Tittle: CMS Outer Tracker Upgrade
Researcher: Bert Harrop (Princeton Staff)

Advisor: Nai Phuan Ong (Physics)
Project Tittle: Nanofabricated Devices Made from Topological Materials
Researcher: Zheyi Zhu (Graduate), Jiayi Hu (Graduate), Bingzheng Han (Graduate)

Advisor: Suzanne Staggs (Physics)
Project Tittle: Detector and Readout for Simons Observatory
Researcher: Logan Ernst (Princeton Staff), Thomas Hanstein (Princeton Staff), Martina Macakova (Princeton Staff)

Advisor: Howard Stone (Mechanical and Aerospace Engineering)
Project Tittle: Micro/Nanotextured Materials, and Microfluidic Systems
Researcher: Samantha McBride (Postdoc); Richard F. Zhu (Undergraduate)

Advisor: Sanfeng Wu (Physics)
Project Tittle: Novel Quantum Devices Based on 2D Materials
Researcher: Sokol Hoxha, (Undergraduate), Tiancheng Song (Postdoc), Yue Tang, (Graduate), Ayelet Uzan (Postdoc), Yu, Guo (Graduate)

Advisor: Ali Yazdani (Physics)
Project Tittle: 2-Dimensional Materials
Researcher: Cheng-Li Chiu (Graduate), Minhao He (Postdoc) Jungwoo Lee (Graduate), Ryan L. Lee (Graduate)

Advisor: Srivatsan Chakram, Rutgers University
Project Tittle: Qubit Fabrication
Researchers: Thomas Dinapoli (Graduate), Jordan Huang (Graduate)

Advisor: Ryan D. Sochol, University of Maryland
Project Title: Nanoscribe GT2 for Bio-Inspired Advanced Manufacturing
Researchers: Adira Leah Colton (Graduate), Declan Fitzgerald (Master's Student Researcher), Kimia Forghani (Graduate); Ziteng Wen; Sunandita Sarker (Postdoc); Olivia Young (Graduate); Xin Xu (Graduate)

Advisor: Anthony Sigillito, University of Pennsylvania
Project Tittle: Silicon Quantum Dots
Researcher: Noah Johnson (Graduate)

Company: SRI
Project Tittle: Device Fabrication
Researcher: Anna Braun, Lewis Haber, Xiaohui Wang,

Company: Sonderrx
Project Tittle: SU8 Process
Researcher: Apeksha Rajamanthrilage, David Hurley

Company: Power Integrations
Project Tittle: Power Transistors
Researcher: Emilia Wrona, Simon Wang