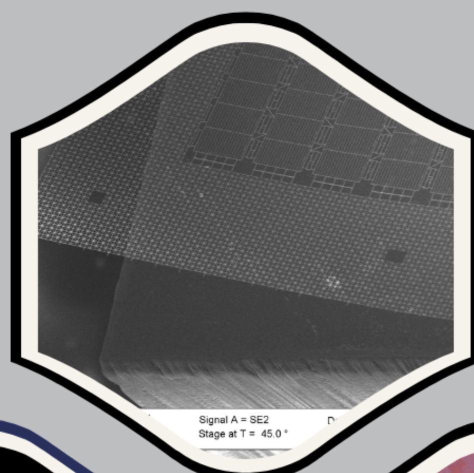
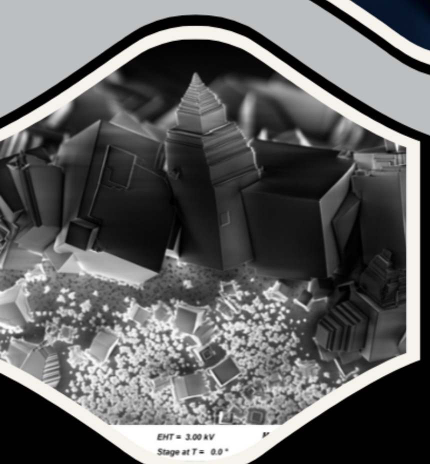
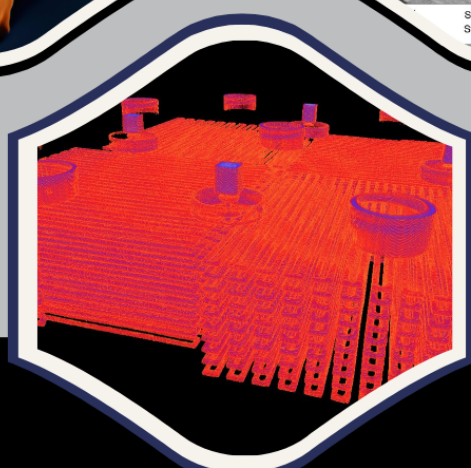
2024 MICROSYSTEMS
ANNUAL RESEARCH REPORT







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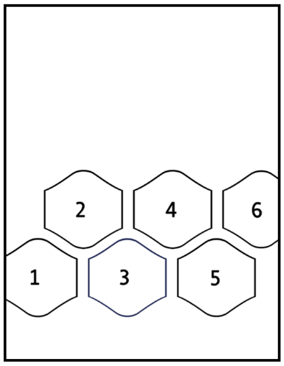

Front Cover Credits

1. “NaCl Crystal Forests,” submitted by Yixuan Jiao, EECS
2. “Wrinkled 3D Nano-Architecture,” submitted by James Surjadi, MechE
3. “M3D-printed Microfluidic Flow Distributor for Multiplexed Electrospray Droplet Thrusters,” H. Kim, L. F. Velásquez-García, p. 78.
4. “A successful fabrication of Silicon Hard Mask for Diamond Waveguide,” submitted by Charles H. Hsu, MTL.
5. “Two-dimentional snowflakes (Graphene flakes on copper film),” submitted by Zhien (Abigail) Wang, DMSE
6. “An insect-scaled bio-inspired flying robot resting on an artificial Calla Lily (Zantedeschia aethiopica). This type of human-friendly mechanical bee is anticipated to assist pollination in challenging environments like Mars.,” submitted by Nemo Yi-Hsuan Hsiao, EECS.

Microsystems Annual Research Report 2024

Director & Editor-in-Chief	Tomás Palacios, Vladimir Bulović
Managing Editors & Project Managers	Meghan Melvin, Jami L. Mitchell
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Foreword

We are pleased to announce the publication of the 2024 Microsystems Annual Research Report, a collaborative effort between the Microsystems Technology Laboratories (MTL) and MIT.nano, covering the academic year from July 1, 2023, to June 30, 2024.

This report highlights the significant achievements of the MIT microsystems community over the past year. In this time, MIT.nano celebrated its 5th anniversary at the Nano Summit on October 24, 2023. Looking ahead, MTL will commemorate the 40th anniversary of its founding on November 20, 2024. As we mark these important milestones, we take pride in showcasing the various ways we continue to drive innovation and advance research in semiconductor materials, technologies, devices, circuits, and systems, as well as exploring new frontiers in nanoscience and nanoengineering. We find ourselves at a pivotal moment in the field of microelectronics, where we are all called upon to push the boundaries of what is possible. MTL, in close partnership with MIT.nano and its state-of-the-art fabrication and characterization facilities, is well-prepared to meet these challenges.

For four decades, MTL has exemplified interdisciplinary and collaborative research, education, and industrial engagement at MIT. This year's report provides a comprehensive overview of over 150 research projects across diverse areas of micro- and nanotechnology. These projects range from advancements in semiconductor materials, the development of new devices, and integrated photonics and circuits, to innovations in insect-scale microrobotics, biomedical systems, and AI hardware accelerators, among many others.

On behalf of MTL and MIT.nano, we extend our deepest gratitude to every contributor to this year's Microsystems Annual Research Report and to the dedicated staff of both organizations, whose tireless efforts have brought this dynamic snapshot of our research to life.

Tomás Palacios
Director, Microsystems Technology Laboratories

Vladimir Bulović
Director, MIT.nano

September 2024

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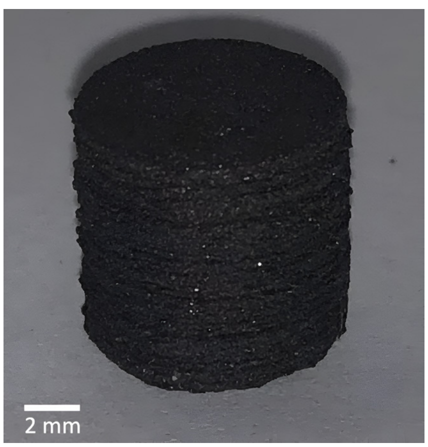
3DHI & Additive Manufacturing

Additively Manufactured Permanent Magnets

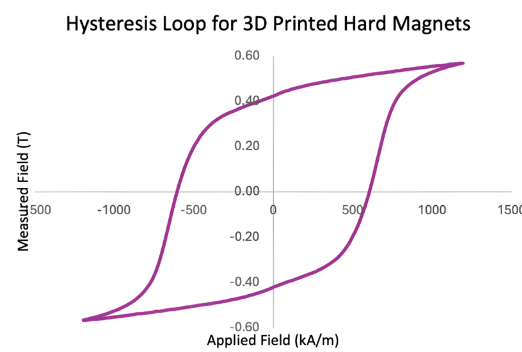
Z. Bigelow, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

Hard magnets are extensively used in numerous industries, including electronics, automotive, renewable energy, healthcare, and consumer goods. However, conventional methods for producing these magnets are limited to simple shapes and require assembly, leading to increased production costs and constrained geometries and devices.

We present a novel three-dimensional (3D) printing process capable of producing hard magnets using micro- and nano-reinforced materials, thereby expanding the scope of their practical applications. Our research focuses on the fabrication of isotropic magnets at a miniature scale, typically ranging in size from a few millimeters. The material composition utilized in our printing process consists of a blend comprising 75% NdFeB and 25% Nylon 12 by volume. Our 3D-printed hard magnets exhibit a measured remanence of 0.423 T, coercivity of 606.7 kA/m, and energy product of 29.5 kJ/m³. These results illustrate the feasibility of 3D printing hard magnets and underscore the potential for fine-tuning magnetic properties through additive manufacturing techniques. These advancements offer precise control over magnet geometry and performance, presenting significant opportunities for industries seeking tailored magnetic solutions.



▲ Figure 1: 3D printed 75% NdFeB magnet.



▲ Figure 2: Hysteresis loop analysis of a 3D printed 75% NdFeB magnet.

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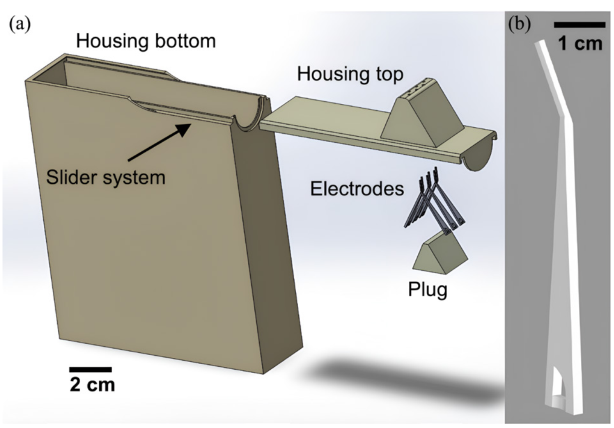
3D-Printed CubeSat Plasma Sensors

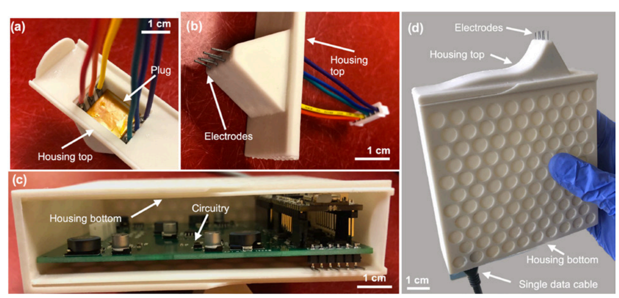
Z. Bigelow, L. F. Velásquez-García
Sponsorship: MIT Portugal

The ionosphere, a critical layer of Earth's atmosphere, is composed of plasma, a qua-si-neutral, superheated state of matter consisting of neutral molecules, ions, and elec-trons. The thermosphere, a region within the ionosphere (ranging 80–600 km above Earth's surface) plays a significant role in global warming. Obtaining accurate plasma measurements in this region has proven challenging since the most reliable data is gathered by satellites orbiting within the thermosphere itself. Given the high cost associated with launching hardware into space, the use of miniaturized satellites, e.g., CubeSats, is an ideal solution to collect ionospheric plasma data. Thus, a strong demand exists for low-cost and compact plasma sensors that can be directly integrated into CubeSats.

We report the design, fabrication, and characterization of a novel, compact, and fully additively manufactured multi-Langmuir probe (MLP) for CubeSat ionospheric plasma diagnostics (Figure 1). The MLP incorporates three different Langmuir probe (LP) arrangements (single, dual, and triple LPs) to accurately measure a wide range of plasma properties with redundancy. The reported MLP has integrated low-power, compact electronics and is manufactured via 3D-printing; consequently, it is a plasma sensing solution compatible with CubeSats that aligns with in-space manufacturing. The dielectric parts of the MLP are made via vat photopolymerization of vitrolite; the conductive parts are made via binder jetting of SS 316L. The electronics of the MLP were verified using calibrated equipment. Experimental characterization of MLP prototypes was conducted using a laboratory helicon plasma chamber and showed good agreement across different LP configurations. The first of its kind, the MLP (Figure 2) enables superior and more affordable CubeSat plasma sensors and aims at providing crucial data to improve understanding of ionospheric plasma and its implications for climate change.



▲Figure 1: (a) Computer-aided design (CAD) exploded view of MLP. Driving electronics are inside housing bottom. Housing top and bottom are assembled using slider mechanism. (b) CAD close-up of LP electrode used in MLP.



▲Figure 2: Selected images of MLP during assembly. (a) Underside of housing top showing plug holding electrodes in place. (b) Top side of housing top showing array of electrodes protruding. (c) Housing bottom with driving circuit inside. (d) Fully assembled device.

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Fully 3D-printed, Three-dimensional Cored Solenoids

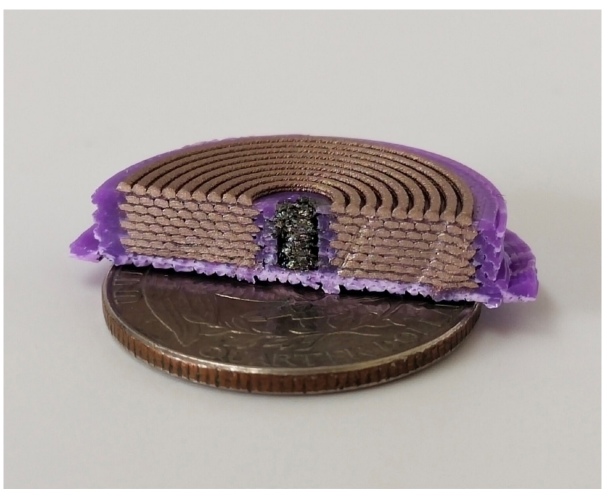
J. Cañada, L. F. Velásquez-García
Sponsorship: Empiriko Corporation, "la Caixa" Foundation

Additive manufacturing can readily produce freeform, mechanically functional parts, including complex systems, e.g., pumps. However, the three-dimensional (3D) printing of electronic components that could enable the monolithic manufacture of integrated electromechanical devices is lagging. Material extrusion, also known as fused filament fabrication (FFF), is an accessible additive manufacturing technique. FFF allows the monolithic fabrication of parts comprising multiple materials, e.g., dielectric and conductive. Reports of 3D-printed resistors, capacitors, and inductors demonstrate the feasibility of 3D-printing electronic components via dielectric- conductive material extrusion. However, the 3D-printed inductors reported in the literature are limited to two-dimensional designs. This work aims to improve the versatility and performance of 3D-printed solenoids by expanding them to truly 3D designs and adding soft magnetic cores.

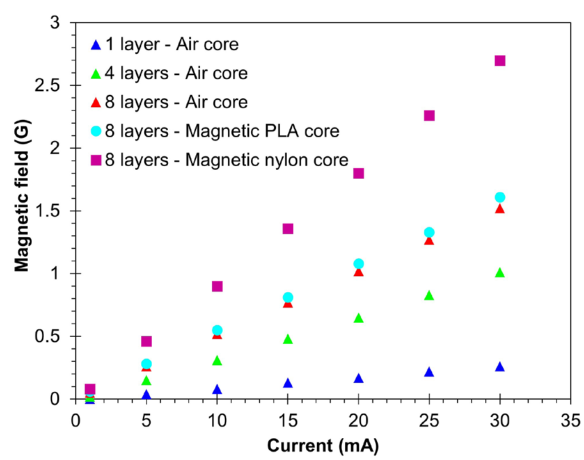
The 3D-printed solenoids have been fabricated through material extrusion using polylactic acid (PLA)- and nylon-based materials: we used dielectric PLA to produce insulation films and structural support features, copper microparticle-doped PLA to create a spiraling conductive trace, and iron-doped PLA and FeSiAl-doped nylon to fabricate soft magnetic cores to be embedded at the center of the structures. By stacking conductive spirals and insulation films, we created truly 3D solenoids (Figure 1).

Magnetic field measurements reveal that 3D-printed solenoids can generate Gauss-level magnetic fields while drawing tens-of-mA currents. The magnitude of the magnetic fields that the solenoids can generate strongly correlates to the number of stacked conductive layers and to the presence of a soft magnetic core. Moreover, an increase in the magnetic permeability of the material used to produce the cores can boost the generated magnetic fields (Figure 2).

This technology is of particular interest for low-cost, low-waste manufacturing of integrated devices and highly customized hardware in remote areas with limited access to resources and manufacturing equipment (e.g., in-space manufacturing).



▲Figure 1: Three-dimensional, monolithically 3D-printed FeSiAl nylon-cored solenoid cut in half, on top of a U.S. quarter.



▲Figure 2: Measured magnetic field vs. current for various 3D-printed solenoids.

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- J. Cañada, H. Kim, and L. F. Velásquez-García "Three-Dimensional, Soft Magnetic-Cored Solenoids via Monolithic, Multi-Material Extrusion," *Virtual and Physical Prototyping*, vol. 19. no. 1, p. e2310046, Feb. 2024. doi: 10.1080/17452759.2024.2310046
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Fully 3D-printed, Semiconductor-free Logic Devices

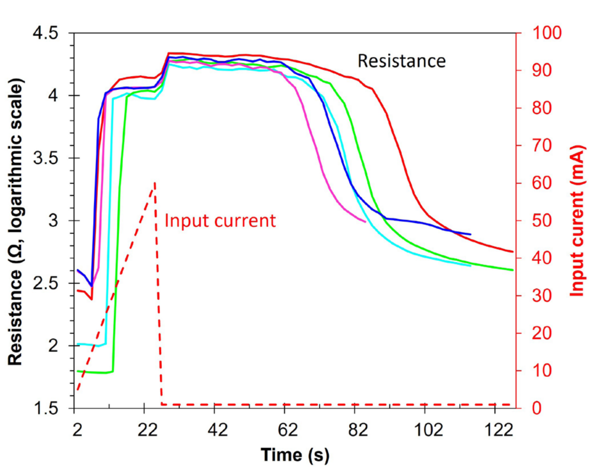
J. Cañada, L. F. Velásquez-García
Sponsorship: Empiriko Corporation, "la Caixa" Foundation

Additive manufacturing technologies can readily produce complex, structurally functional parts, including complex microfluidics. There are also reports of three-dimensional (3D)-printed, passive electronic components (e.g., resistors, capacitors, inductors) and electromechanical devices, including sensors and actuators. However, the 3D printing of active electronics with control and processing capabilities remains a challenge. As a result, the integration of additively manufactured electromechanical devices necessarily relies on off-the-shelf components and integrated circuits to produce functional, controllable systems.

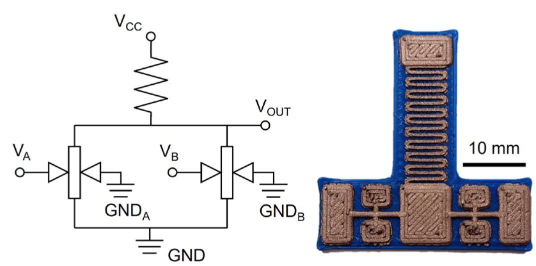
This work reports the first proof-of-concept demonstration of fully 3D-printed, semiconductor-free active electronic devices. The devices are fabricated via material extrusion—one of the most accessible 3D printing technologies. Material extrusion creates parts by heating up feedstock and pushing it through a nozzle, constructing parts layer by layer; it is one of the few additive manufacturing technologies that allows monolithic multi-material fabrication.

The active electronic devices have been fabricated combining dielectric polylactic acid (PLA) (as substrate) and copper-reinforced PLA. The devices take advantage of a newly discovered reversible fuse-like behavior exhibited by narrow 3D-printed traces of copper-reinforced PLA: when a high-enough current is applied to a trace, its resistance spikes by orders of magnitude; after it cools down, its resistance drops to its original range (Figure 1). Harnessing this phenomenon, we created a switching device qualitatively comparable to a p-channel metal-oxide semiconductor transistor to use as a building block to implement fully 3D-printed, semiconductor-free logic gates (Figure 2).

This technology allows the monolithic fabrication of electromechanical devices integrating simple control and data processing functions and can enable the additive manufacture of fully functional, intelligent devices, right off the printer bed. The technology holds particular interest for low-cost, low-waste manufacturing of integrated devices and highly customized hardware in remote areas with limited access to resources and manufacturing equipment (e.g., in-space manufacturing).



▲Figure 1: Resistance of narrow 3D-printed traces of copper-reinforced PLA (solid lines) when subjected to ramp up current (dashed line) and then allowed to cool down. Voltage limited to 30 V.



V_{CC} (V)	V_A (V)	V_B (V)	V_{OUT} (V)
6	0	0	0.03
	0	20	0.08
	20	0	0.73
	20	20	5.3

▲Figure 2: Fully 3D-printed AND gate: schematic (top left), picture of fabricated device (top right), and input/output signals (bottom).

FURTHER READING

- J. Cañada and L. F. Velásquez-García, "Fully 3D-printed, Semiconductor-free, Transistor-like Logic Devices," *22nd International Conference on Solid-State Sensors, Actuators and Mi-crosystems* (TRANSDUCERS), Kyoto, Japan, 2023.
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Additively Manufactured Quadrupole Mass Filter with Unity Mass Resolution

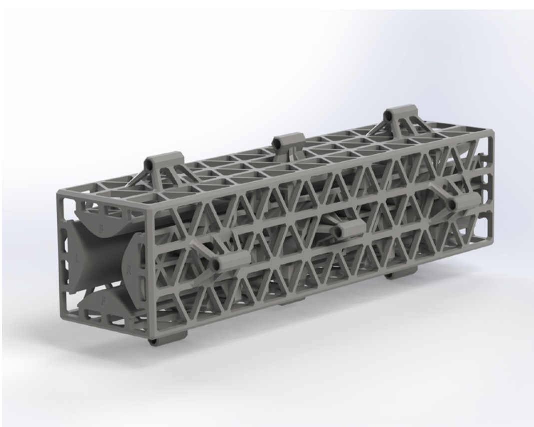
C. Eckhoff, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

Mass spectrometry is a crucial analytical technique in any field that works with chemistry. The heart of a mass spectrometer is the mass filter, a structure that sorts species based on their mass-to-charge ratio. There have been numerous efforts to miniaturize and reduce the cost of mass filters to broaden the range of applications of mass spectrometry.

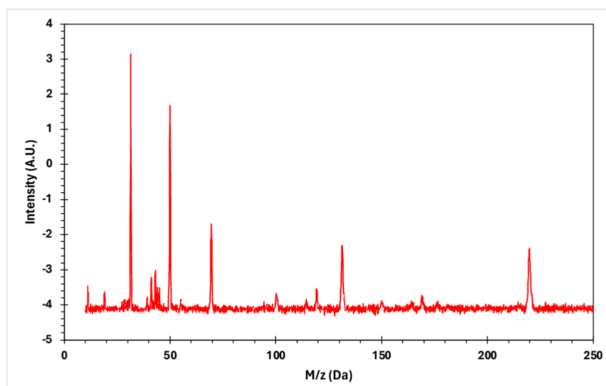
A quadrupole mass filter (QMF) is a popular choice for a mass filter due to its sturdiness, mass range, resolution, and sensitivity. Unfortunately, miniaturizing QMFs usually significantly compromises their performance because high-quality QMFs require high relative manufacturing precision. We have successfully approached this problem by employing advanced additive manufacturing to make a lower-cost, lighter-weight QMF that still boasts exceptional performance for practical mass spectrometry.

Our devices feature a monolithic and skeletonized design, integrating all four electrode rods into a single piece for precise alignment and reduced assembly needs. This design not only cuts production costs, but also creates lightweight components. Utilizing digital light processing (DLP) of glass ceramics, we printed the QMF geometry, which is then selectively metallized with electroless nickel-boron plating. To ensure electrode isolation, a lacquer-based maskant was applied at specially designated points—imperative for monolithic designs. One of our QMFs requires 10s of U.S. dollars in materials and takes about a day to manufacture.

Mass spectra experiments showcase well-resolved peaks with full width at half maximum (FWHM) of 0.7 Da or less at 69 m/z (the threshold of unity mass resolution). These exciting results bolster the potential of additive manufacturing to create portable mass spectrometers and other next-generation scientific instruments. Our primary focus now falls on further enhancing the device's performance to be compatible with isotope detection and increased mass range.



▲ Figure 1: Rendering of device, showcasing monolithic fabrication and skeletonized architecture.



▲ Figure 2: Scan of PFTBA with unity mass resolution at 69 m/z.

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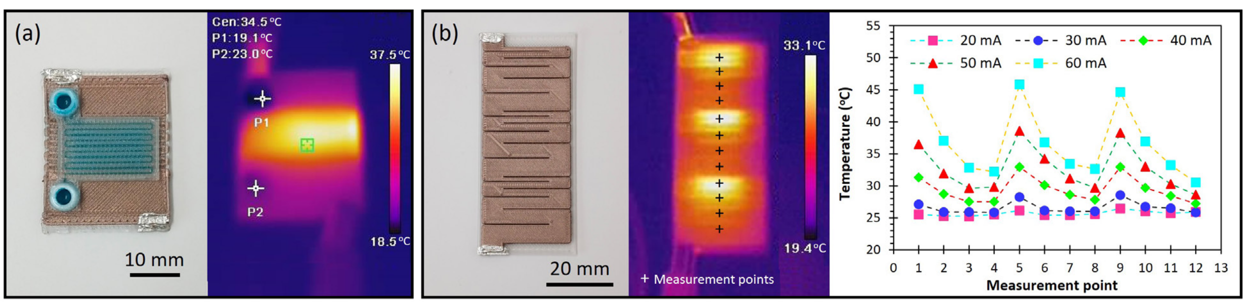
Additively Manufactured, Monolithic, Self-Heating Microfluidic Devices

J. Cañada, L. F. Velásquez-García
Sponsorship: Empiriko Corporation, "la Caixa" Foundation

Temperature regulation is critical in many microfluidic applications, e.g., to sustain living organisms, to trigger specific chemical reactions. Temperature regulation techniques often involve the use of bulky equipment, and integrated cooling-heating systems rely on costly fabrication processes.

We propose the use of multi-material extrusion 3D printing to create monolithic, self-heating microfluidic devices. The proof-of-concept devices are fabricated using two polylactic acid-based materials: one dielectric, used to produce the microfluidic channels; and one conductive, used to fabricate heat-generating resistors. The ability of material extrusion to create custom, intricate patterns enables the fabrication of complex, application-specific designs of both the microfluidic structure and the heating system. This technology can greatly impact the yield of microfluidic research by enabling the fast, inexpensive, in-house fabrication of custom, self-heating microfluidic devices.

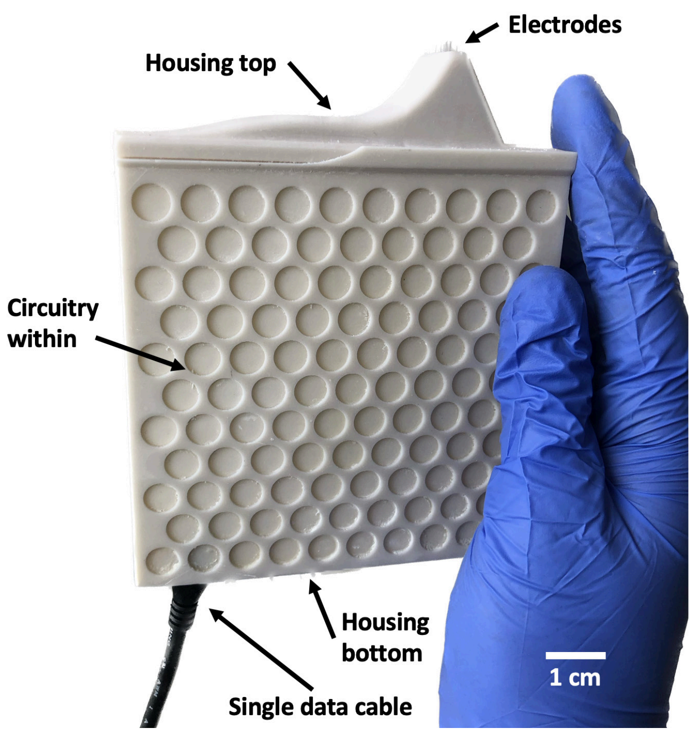


▲ Figure 1: (a) Optical and thermal images of a 3D-printed, self-heating microfluidic device, and (b) Optical and thermal images, and measured temperature profiles of a custom 3D-printed heater.

Miniature 3D-Printed Super Sensor: Multi-Langmuir Probe Device for CubeSat Ionospheric Plasma Diagnostics

Z. Bigelow, L. F. Velásquez-García
Sponsorship: MIT Portugal, NewSat Flagship Project

The ionosphere is a plasmic part of Earth's atmosphere which affects climate change. Studying it requires satellite based in-situ measurements and the versatility of Langmuir probes make them ideal for this. We report the design, fabrication, and characterization of a compact, fully 3D printed, multi-Langmuir probe (MLP) for use on CubeSats. The MLP has low-power, compact electronics and is fully 3D printed, to be compatible with in-space manufacturing. The MLPs are made via vat photopolymerization of vitrolite for the dielectric parts and binder jetting SS 316L for the conductive parts. The MLP uses three different Langmuir probe arrangements (single, dual, and triple) to measure a wide range of plasma properties with redundancy. The MLP was tested in a helicon plasma chamber, showing good agreement across the different configurations. This MLP enables cheaper CubeSat plasma sensors and aims at improving our understanding of the ionosphere and its effects on climate change.



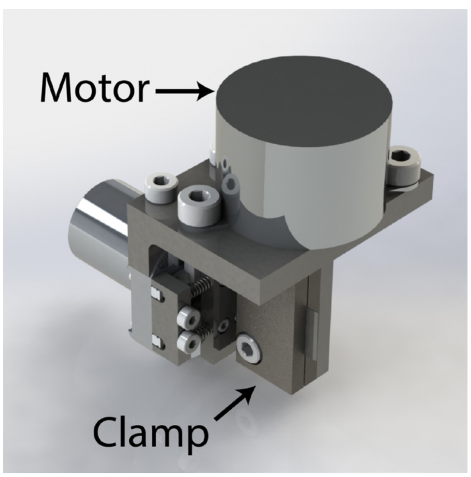
▲ Figure 1: MLP device fully assembled, with relevant parts labelled.

High-precision Adhesion Measurements for Heterogeneous Lintegration

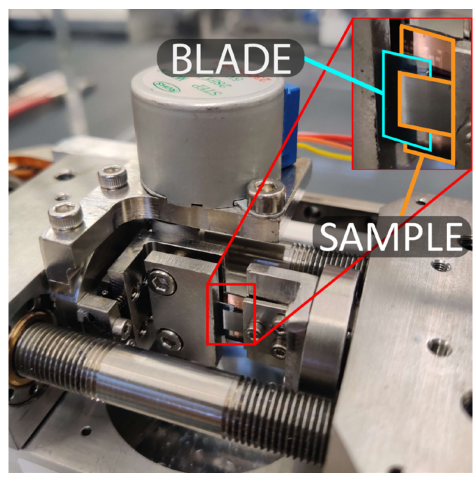
A. T. Wang, C. C. Tasan, C. V. Thompson
Sponsorship: SRC/DARPA, Mitsubishi Materials Corporation

Advances in computing power require rapid development of new materials and processes for heterogeneous integration with two-and-a-half dimensional (2.5D) and three-dimensional (3D) architectures. These architectures require bonding between integrated circuits (ICs) fabricated as separate dies that are interconnected with high densities of electrical interconnects. From a reliability perspective, these bonds may pose an issue since thermomechanical stresses may cause delamination. To assess this risk, adhesion tests must more accurately quantify the strength of the bonds, or more specifically, the work of adhesion. This term represents the energy required to de-bond a sample, which includes any plastic work from permanent deformation and elastic energy released from crack propagation. Ideally, characterization of specific failure mechanisms would be carried out through in situ mechanical testing in scanning electron microscopes (SEMs).

We considered several adhesion measurement tests and selected the wedge test based upon sample size limitations and measurement precision. The wedge test involves inserting a blade between the bonded samples and observing the delamination. The drawback of the wedge test is that it is typically done by hand, which often leads to imprecision. We have resolved this issue by designing and building a setup which can allow the test to be done with a deformation stage. The stage is designed for tensile/compressive testing of small samples and therefore has high force resolution (0.02 to 2000 N) and controlled constant displacement rates (0.1 to 20 µm/s). Furthermore, the deformation stage can be put inside an scanning electron microscope (SEM), which allows for high resolution observations of de-bonding mechanics. The setup also allows for alignment of the blade and the sample within the SEM using a cam-style linear actuator. We performed a proof-of-concept test with the setup. Figure 1 shows a computer model of one side of the designed parts; and Figure 2 shows an SEM micrograph of the proof-of-concept test. GoMoving forward, we plan ton working with university and industry collaborators to begin testing complex bonded structures.



▲ Figure 1: One side of the designed setup consisting of a clamp to hold the blade and a motor connected to a cam twhichat can move the clamp left and right to precisions within one micrometer.



▲ Figure 2: Proof-of-concept of the wedge test with an insert depicting a closer view of the blade being inserted into a bonded sample.

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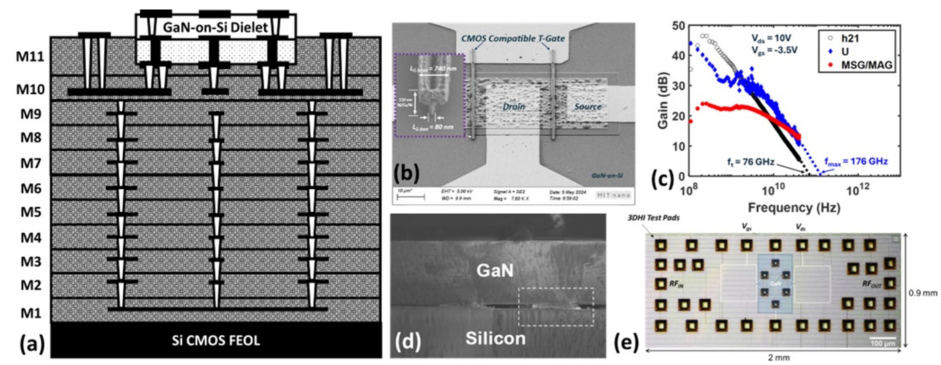
Development of a GaN/ Si CMOS Stacked-3DIC Platform for W-band Applications

P. Yadav, J. Niroula, Q. Xie, R. Han, T. Palacios

Sponsorship: United States Air Force Office of Scientific Research (Grant No. FA9550-22-1-0367), SRC JUMP 2.0 (Grant No. 2023-JU-3136), Lockheed Martin Corp. (Grant No. 025570-00036), Advanced Research Projects Agency-Department of Energy (Grant No. DE-AR0001591), and National Defense and Science Graduate Fellowship

With data rates pushing into the Tbps for augmented/virtual reality, there is an urgent need for the use of sub-terahertz radio-frequency (RF) front ends and transistors. GaN transistors are an ideal candidate for the front-end-of-line (FEOL) as they push the limits of high-power density, high frequency semiconductor devices. Further, Si is an ideal candidate for the back-end-of-line (BEOL) due to ease of manufacturing and access to complementary logic technology for digital circuits.

In this system, three-dimensional (3D)-stacked GaN dielets, are connected via highly scaled interconnects to the Si BEOL. The dielet is optimally placed to ensure uniform and minimal thermal degradation in the system. This approach will yield a bespoke chip design, tailor-made for the given high-speed application. To design the most efficient high data rate communication systems, we have embraced a design/system-technology co-optimization (DTCO/STCO) approach that combines a highly scaled W-band GaN dielet technology featuring a novel Cu-based gate metallization, with state-of-the-art Intel16 22-nm Si bias and control circuitry, via Cu-Cu 3D-heterogeneous integration.



▲Figure 1. 3DIC building blocks and key technology nodes. (a) 3DIC integration schematic with GaN dielet leveraging Si complementary metal-oxide semiconductor (CMOS) BEOL (b) 80-nm CMOS-compatible t-gate high-electron-mobility transistorytransistor (HEMT) technology in 200-mm sourced GaN-on-Si (c) W-band RF performance of scaled GaN-on-Si HEMT with CMOS-compatible gate (d) Cross section scanning electron microscopy of GaN/Si CMOS Cu-CU bonding interface. (e) Chip micrograph of Intel16 BEOL circuit.

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Circuits and Systems

RAELLA: Reforming the Arithmetic for Efficient, Low-Resolution, and Low-Loss Analog PIM: No Retraining Required!

T. Andrulis, J. S. Emer, V. Sze
Sponsorship: Ericsson, MIT AI Hardware Program, MIT Quest

Processing-In-Memory (PIM) accelerators have the potential to efficiently run Deep Neural Network (DNN) inference. By computing directly inside memory, PIM accelerators avoid expensive off-chip movement of the DNN weights. Furthermore, PIM accelerators often utilize Resistive-RAM (ReRAM) devices and ReRAM crossbars for dense and efficient analog compute.

Unfortunately, while ReRAM crossbars can compute efficiently and with high density, overall PIM accelerator energy is often dominated by the analog-to-digital converters (ADCs) that read computed analog values from crossbars.

Some prior works attempt to reduce this ADC overhead by changing or pruning DNN weights. This reduces computations and ADC converts required, but also introduces accuracy loss. Other works use efficient lower-resolution ADCs to process high-resolution analog values from crossbars, but the resolution difference introduces error and also leads to accuracy loss. Unfortunately, this accuracy loss require costly DNN retraining to compensate for, which is not always possible.

To address high ADC costs without requiring retraining, we propose the RAELLA architecture. RAELLA adapts the architecture to each DNN; it lowers the resolution of computed analog values by encoding weights to produce near-zero analog values, adaptively slicing weights for each DNN layer, and dynamically slicing inputs through speculation and recovery. Low-resolution analog values allow RAELLA to both use efficient low-resolution ADCs and maintain accuracy without retraining, all while computing with fewer ADC converts.

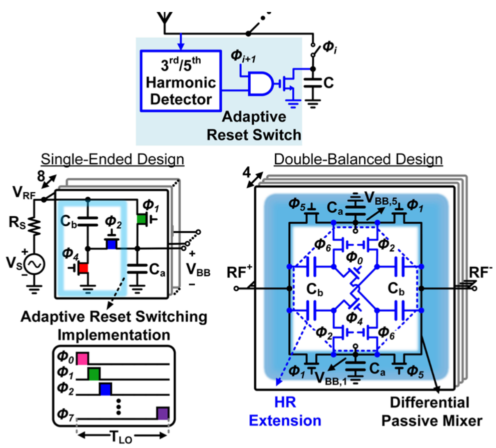
Compared to other low-accuracy-loss PIM accelerators, RAELLA increases energy efficiency by up to 4.9× and throughput by up to 3.3×. Compared to PIM accelerators that cause accuracy loss and retrain DNNs to recover, RAELLA achieves similar efficiency and throughput without expensive DNN retraining.

Implementation and Application of Adaptive Reset Switching for Harmonic Rejection in Passive Mixers

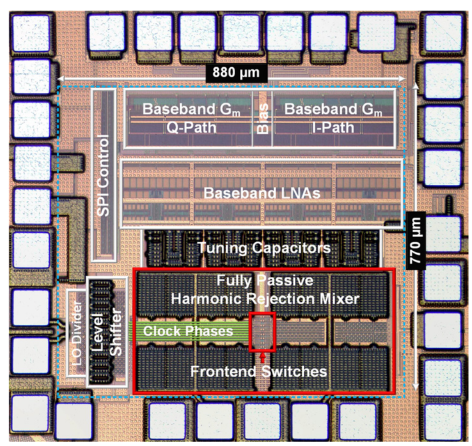
S. Araei, S. Mohin, N. Reiskarimian

Wireless communication systems benefit from software-defined radios (SDRs) that can seamlessly switch across multiple standards without relying on cumbersome filters. The hard switching passive mixer is a key enabler for such receivers by facilitating on-chip tunable filtering. Utilizing a mixer-first receiver architecture to apply such filtering at the antenna interface is effective against near-band blockers but falls short against far-out blockers, particularly harmonic blockers. Interferers around the harmonics of the local oscillator are down-converted along with the desired signal, receive the same amplification, and can saturate the entire receiver. To maximize harmonic blocker tol-erance in mixer-first designs, suppressing harmonic blockers right at the antenna is crucial, similar to how near-band blockers are attenuated.

In this work, we propose an adaptive reset switching technique that effectively distin-guishes between desired signals and harmonic blockers. If the circuit detects a base-band signal originating from harmonic blockers, it immediately shunts the charge to ground. Otherwise, it leaves the signal intact, ensuring minimal impact on the system's noise figure. The co-design of top-plate and bottom-plate mixing enables a fully passive and low-loss implementation of this adaptive reset switching, achieving harmonic rejection at both the antenna interface and the baseband nodes. This proposed harmonic filtering technique requires no additional circuitry beyond extra switches and benefits from technology scaling. The fabricated 45-nm silicon-on-insulator (SOI) prototype receiver, occupying an active area of 0.68 mm², operates across a broad frequency range from 250 MHz to 4 GHz. It tolerates +14.5 dBm and +16 dBm for 3rd and 5th harmonic blocker powers, respectively; this is 100 times greater than state-of-the-art broadband receivers that utilize active harmonic rejection. Such high linearity, combined with the seamless integration of adaptive reset switching into legacy mixer-first receivers, paves the way for next-generation universal radios.



▲Figure 1: Concept of adaptive reset switching and its single-ended and double-balanced implementation.



▲Figure 2: Die micrograph of the proposed harmonic rejection receiver.

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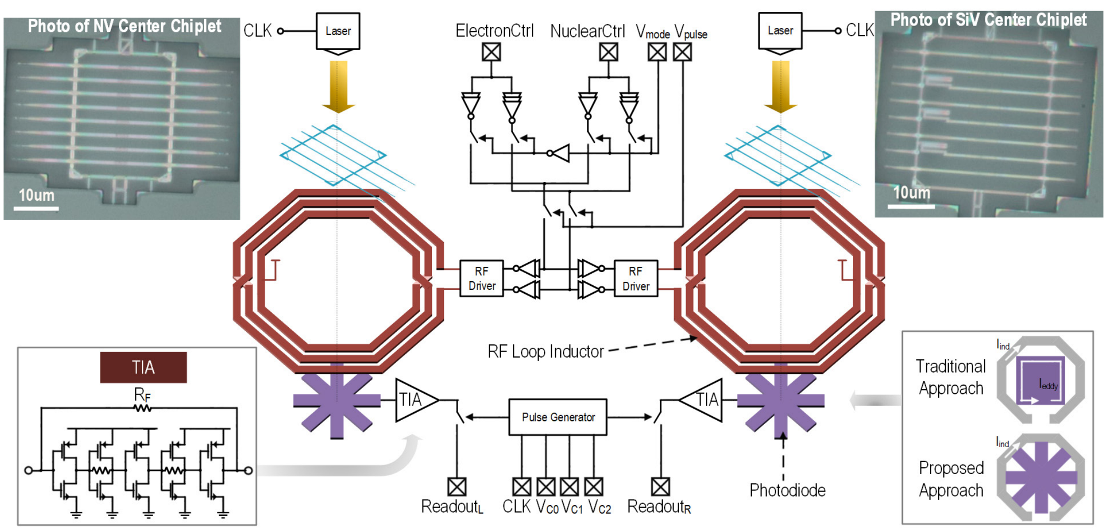
A CMOS-Integrated Color Center Pulse-Sequence Control and Detection System

J. Wang, I. B. Harris, X. Chen, D. R. Englund, R. Han
Sponsorship: Intel University Shuttle, Jet Propulsion Laboratory

We introduce a CMOS-integrated control and detection system capable of functioning at both room and cryogenic temperatures, for accommodating general color centers. The chip encompasses a radio frequency driver comprising two inductors, designated for electron/nuclear spin within two diamond samples. The chip incorporates readout circuitry equipped with photodiodes fashioned in the shape of Union Jack patterns to reject the eddy current. To facilitate fluorescence detection while mitigating the impact of passivation fluorescence and laser excitation, a tunable pulse generator is implemented within the readout system. This configuration enables the acquisition of fluorescence data of color centers in the time domain subsequent to the deactivation of the laser pulse. Since the lifetime of the red fluorescence emitted by the passivation layer is much shorter than that of any types of color centers, the chip no longer requires post-processing such as reactive-ion etching to remove the passivation.

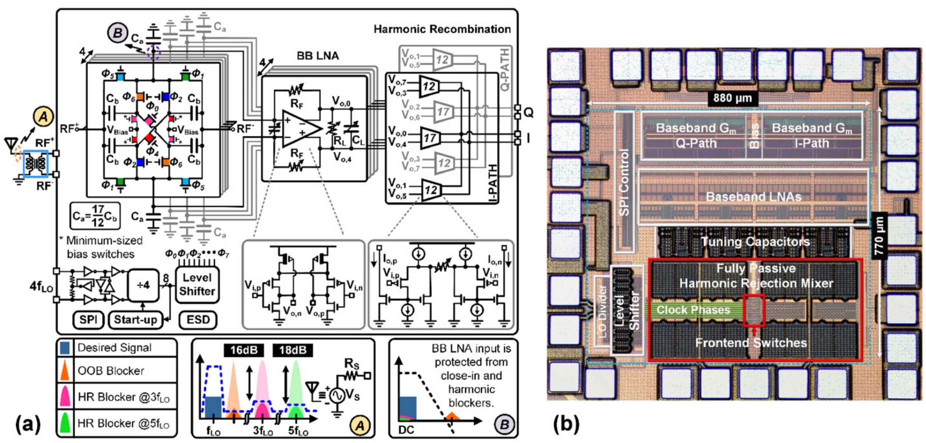


▲ Figure 1: Block Diagram of Control and Readout Circuit

An Enhanced Harmonic-Tolerant Mixer-First Receiver Employing Concurrent Top and Bottom-Plate Mixing for 5G NR Applications

S. Araei, S. Mohin, N. Reiskarimian

The demand for stringent linearity in modern receivers, crucial for supporting 5G New Radio (NR), along with the aspiration to eliminate the reliance on off-chip Surface Acoustic Wave (SAW) filters, drove the preference for mixer-first receivers over the past decade. These structures, however, are vulnerable to harmonic blockers, posing a significant challenge to their design. In this work, we introduce a low-loss fully passive harmonic rejection (HR) mixer that concurrently uses top and bottom-plate mixing linked with a readout switch. The LO filtering in this design not only delivers HR at the mixer's output but also promptly suppresses harmonic blockers at the antenna interface, ensuring high linearity. Moreover, this HR technique requires only a few switches and capacitors, making it scaling-friendly and leading to extended frequency operation and superior noise performance compared to existing state-of-the-art HR mixers, positioning it as a strong candidate for 5G NR applications.



▲ Figure 1: (a) Block diagram of the proposed architecture (b) Die Micrograph

A Scalable Cryogenic Phased Array Feed for Radio Astronomy with Integrated Continuous Calibration

D. Sheen, F. Lind, R. Han
Sponsorship: NSF SpectrumX (SII-2132700), Intel University Shuttle Program

The rapid growth of mobile communications platforms poses an increasing challenge for radio astronomy and radio science instruments. As broadband communications technologies push into millimeter wave ranges, scientific receivers that once operated in clear spectrum must now contend with sources orders of magnitude stronger than the signals they are designed to observe. The next generation of radio telescopes and radiometers need to be dynamic instruments capable of adaptive spatial and spectral filtering of measurement data while maintaining calibration in a strong signal environment. Phased arrays can offer these capabilities, but their noise performance and cost scaling with aperture size render them impractical for microwave radio astronomy.

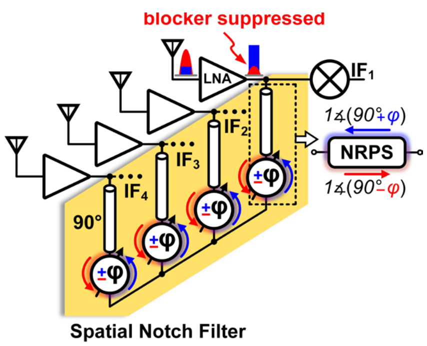
In this work, we propose a hardware architecture for a new generation of scalable high dynamic range phased array feeds for reflector telescopes to address theses challenges. This approach promises to overcome many of the scaling limits of traditional phased arrays. A technology demonstration is planned for the Westford Radio Telescope.

A Blocker-tolerant mm-Wave MIMO Receiver with Spatial Notch Filtering Using Non-reciprocal Phase-shifters for 5G

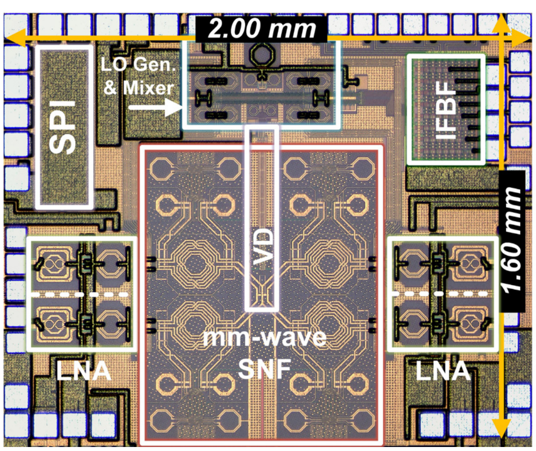
S. Mohin, S. Araei, M. Barzgari, N. Reiskarimian

Millimeter-wave beamforming receivers (RX) have become increasingly popular for their ability to enhance spectral efficiency, improve signal-to-noise ratio, and enable multiple-input multiple-output (MIMO) operations. Analog beam-formers contribute to spatial blocker suppression at the RX front-end, thus protecting the analog-to-digital converter (ADC) from strong spatial blocker signals. In contrast, digital beamformers generate multiple output streams and allow for flexible digital calibration. They are more compact and energy-efficient than hybrid beamformers. However, digital beamformers are vulnerable to strong signal interference and necessitate a high RX/ADC dynamic range and linearity to avoid saturation. To address this challenge, various techniques have been developed to establish spatial notch filters (SNFs) that selectively eliminate interference from certain incident angles.

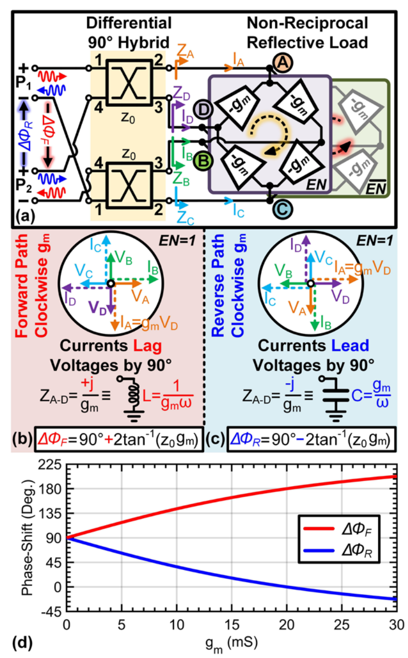
We present a highly linear SNF architecture that supports N-input-N-output MIMO systems. Our design employs low-loss nonreciprocal phase-shifters (NRPSs) to directly suppress spatial blockers at the outputs of low noise amplifiers (LNAs), thus targeting blockers at the earliest stage within the RX chain. This architecture offers significant advantages over previous designs by: (I) enhancing RX linearity through the rejection of blockers at the LNA outputs, achieving an in-notch input P1dB of -7.8 dBm and (II) enabling the SNF to be completely deactivated in the absence of spatial blockers, which reduces power consumption and the noise impact of the SNF components.



▲Figure 1: The proposed Receiver with SNF.



▲Figure 2: Die micrograph.



▲Figure 3: (a) Circuit implementation of NRPS. Equivalent loads for clockwise set of transconductances in (b) forward path, and (c) reverse path.

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Millimeter-wave Phased-array Radar for Vital Sign Detection

S. Sabouri, N. Reiskarimian, A. P. Chandrakasan

Cardiovascular diseases have been the leading cause of death globally, as outlined by the World Health Organization (WHO). Continuous monitoring of heart rate and respiration is crucial in diagnosing and treating these diseases; hence any advancements in monitoring are invaluable.

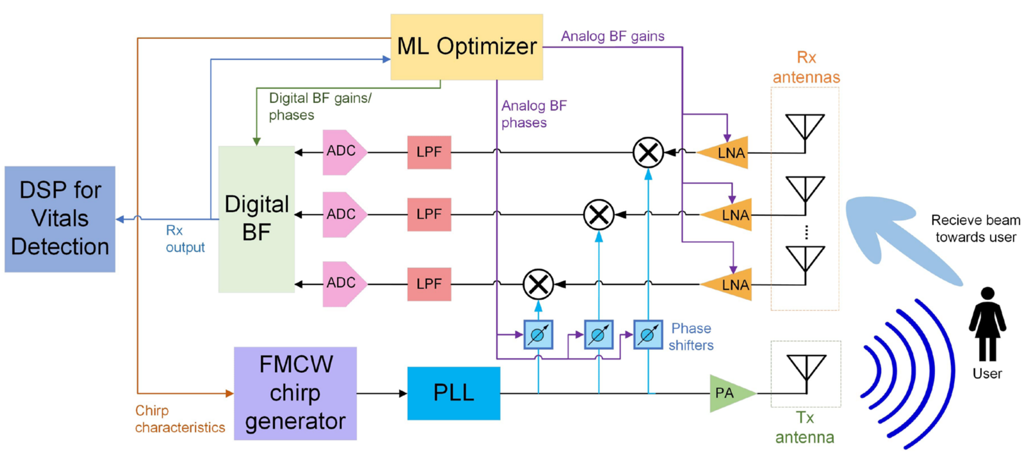
The aim of this project is to use radar technology for continuous, in-home healthcare monitoring of vulnerable populations, including the elderly and individuals with chronic illnesses. The advancements in wireless sensing, communications, and radar technologies enables contactless detection of vital signs, such as respiration and heart rate.

The proposed radar system for vital-sign detection transmits a radio frequency (RF) signal towards a user and measures the time it takes for the signal reflected off the patient to arrive back to the device: the periodic displacements of the chest due to breathing and heartbeat affect the time of arrival and can be measured by the radar. However, most radars for vital signs in the prior work are made with discrete components and operate at frequencies below millimeter-wave, limiting the performance and precision in measurements. Thus, the goal of the project is to develop a millimeter-wave phased-array radar integrated circuit for improved, multi-user detection of human respiration and heart rate.

This radar architecture will use beamforming techniques to improve the vital signal quality by receiving the reflected RF signal in a directed beam towards the target. To accurately collect vital sign data from a target even as they move within a room, an adaptive beamforming algorithm will be implemented on an FPGA, steering the beam to track the target's location.

Solving for the multi-variable beamforming parameters is a computationally intensive and non-convex optimization problem. To mitigate this issue, a machine learning (ML) model will be used to optimize the beamforming and radar parameters such as the phases and gains of antenna elements, beamwidth, and chirp characteristics to maximize performance.

Ultimately, there will be a tapeout of this novel RF integrated circuit (IC) radar system on a chip. To implement the beamforming capabilities, the chip will include a millimeter-wave phased-array front-end. A fractional-N phase locked loop (PLL) will be used to generate the frequency-modulated continuous wave (FMCW) chirp waveform for each RF channel in the phased-array.



▲Figure 1: Proposed millimeter-wave radar for vital sign detection block diagram. Architecture includes phased-array RF front end integrated circuit (IC), digital beamformer (BF) block, DSP block, FMCW chirp generator, PLL, and ML optimizer to find op-timal beamforming and chirp parameters.

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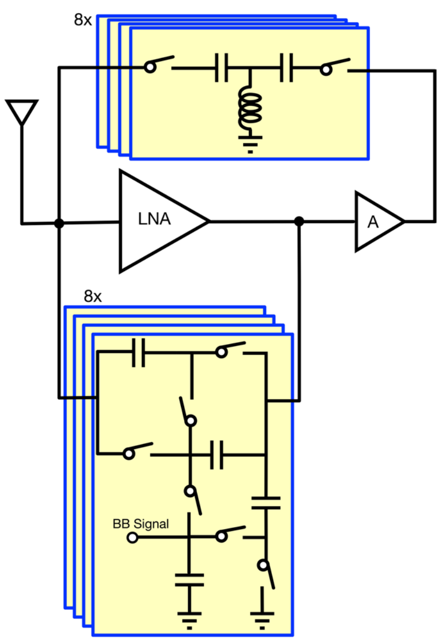
A Sub-6GHz Configurable Receiver with 3rd-order Channel Selectivity and Harmonic Rejection

H. Yang, N. Reiskarimian

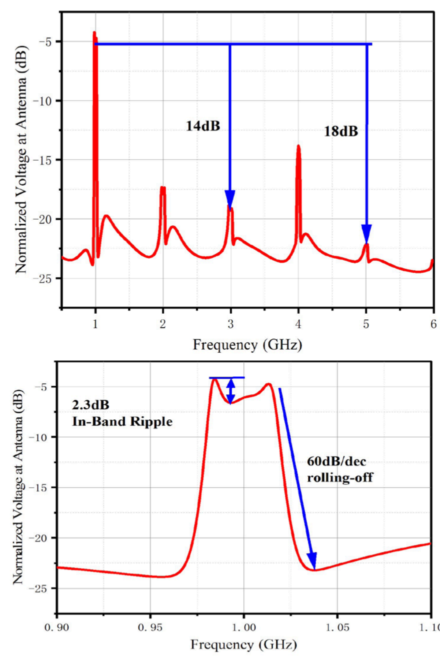
As the sub-6G spectrum becomes increasingly congested with applications such as 5G New Radio, Bluetooth, and wireless local-area networks (WLAN), it is crucial for receivers to exhibit sharp filtering and resilience against out-of-band blockers, including harmonic and close-in blockers. Additionally, user equipment can benefit from the flexibility of the carrier frequency and bandwidth to support multiple communication standards with a single device, such as software-defined radios (SDRs). The conventional mixer-first receiver offers a surface acoustic wave-less, highly linear, and configurable solution, but it is vulnerable to harmonic blockers and has a poor noise figure.

In this work, we propose a configurable receiver tolerant to both harmonic blockers and close-in blockers, with all blockers rejected and 3rd-order filtering directly at the antenna. As shown in Figure 1, the proposed design combines a low-noise amplifier (LNA) with Miller harmonic rejection mixer and a 3rd-order notch filter feedback. With the LNA and the second layer of harmonic rejection mixer, the obtained baseband signal has a decent noise figure and blocker 1-dB compression point (B1dB).

This design will be implemented in Taiwan Semiconductor Manufacturing Company 65-nm technology. The simulated profile of the normalized antenna voltage response is shown in Figure 2.



▲ Figure 1: Figure 1: Architecture of the proposed receiver.



▲ Figure 2: Voltage response at antenna node based on schematic simulation results.

Electronic, Magnetic & Spintronic Devices

Design-technology Co-optimization of 2D Electronics

A. Yao, J. Zhu, T. Palacios
Sponsorship: SRC Jump 2.0 SUPREME Center

With 2D electronics becoming more mature in both material synthesis and device integration techniques, Design-Technology Co-Optimization (DTCO) has been used in designing complex electronic devices based on 2D materials and optimizing device performance and material properties. However, there still lacks an efficient electrical characterization method to provide real-time evaluation and accurate feedback for every process step from material growth to device fabrication. Meanwhile, it is also critical to conduct compact, accurate device modeling especially for high-performance transistors with scaled channel length.

In this project, we investigated fast electrical characterization methods based on circular transmission line model (CTLM) structure. We developed a parameterized cell (PCell) to aid CTLM layout design and fabricated global back-gated devices with both transferred and directly-grown 2D thin films. The convenience of only one lithography step allows seamless switches between different combinations of dielectric layers, metal contacts and passivation layers. The samples were examined by scanning electron microscope (SEM) and contour detection algorithms were used to identify the fabrication-induced variation, domain size, effective channel length and width. These data offered experimental calibration for precise device modeling, which later contributed to design and performance predictions based on TCAD simulation. Simulation models were further studied focusing on highly-scaled transistors with channel length below 10 nm. We expect this fabrication, characterization and modeling pipeline to ultimately facilitate future DTCO processes with improved efficiency and accuracy for novel materials and devices.

Ohmic Contacts to Ultrawide-Bandgap Two-Dimensional Semiconductors

A. S. Gupta, J. Zhu, T. Palacios
Sponsorship: Army Research Office (ARO)

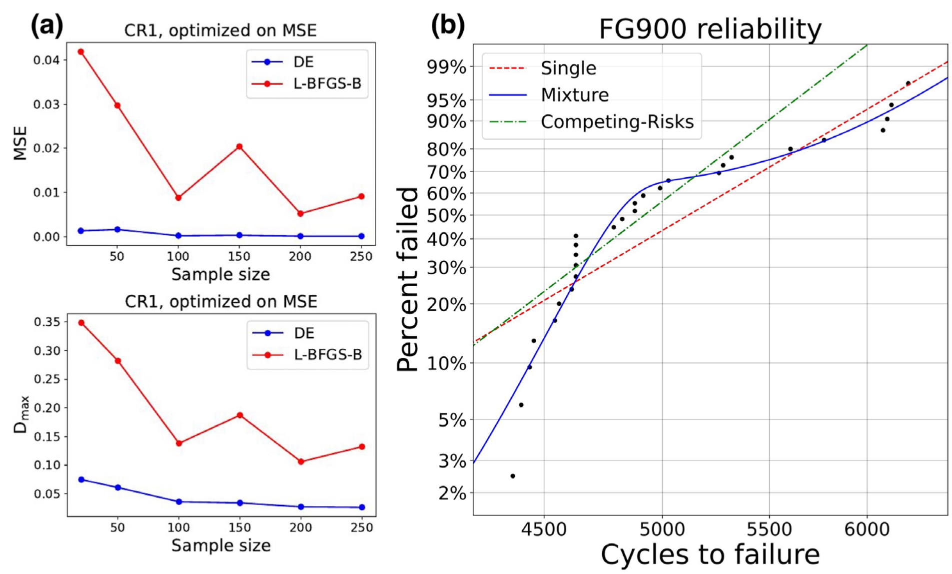
Power transistors for fast switching high voltage applications require wide bandgaps to enable large breakdown fields. Silicon carbide (SiC) and gallium nitride (GaN) thus offer advantages over silicon for high-voltage devices and circuits. However, these materials still have limited bandgaps (~3.5 eV) and are difficult to integrate with circuits based on other material systems. The emerging ultrawide-bandgap (UWBG) two-dimensional (2D) semiconductors, which have bandgaps above 5 eV, are expected to provide even better performance thanks to their wider bandgaps, higher critical fields, and atomic thinness. However, forming ohmic contacts to UWBG 2D materials such as hexagonal boron nitride (h-BN) and 2D GaN is very challenging due to their extreme band misalignment with metal contacts, difficulties in realizing substitutional doping, and the Fermi level pinning effect.

Here, we investigate potential approaches to forming ohmic contacts to UWBG 2D semiconductors. Modulation doping can be used to introduce more carriers to the transistor channel without significantly deteriorating carrier mobility. Dipole moments, graded 2D heterostructures, and highly-doped UWBG oxides, are all investigated to tune both the contact metal work function and the band edge of UWBG semiconductors. A combination of these techniques can be used to form ohmic contacts to UWBG 2D materials, thus enabling the next generation of power electronic devices with higher operation voltage as well as future integrated circuits with increased functionalities.

Identification of Multiple Failure Mechanisms for Device Reliability Using Differential Evolution

U. Chakraborty, E. Bender, D. S. Boning, C. V. Thompson
Sponsorship: SRC

Assessing the reliability of electronic devices, circuits, and packages requires accurate lifetime predictions and identification of failure modes. However, the common assumption of a single failure mechanism usually leads to inaccurate reliability estimates. In this work, we demonstrate a new method for extracting underlying failure mechanism distribution parameters from data corresponding to a combined distribution of two distinct failure mechanisms. The failure mechanisms can be mutually exclusive and acting on different components (mixture model), or simultaneously acting on the same component (competing-risks model). We implement differential evolution (DE) for parameter identification in both competing-risks and mixture models and show that it out-performs the best-known method in the literature, the limited-memory Broyden–Fletcher–Goldfarb–Shanno (L-BFGS-B) approach, especially at small sample sizes (Figure 1a). On industrial ball grid array reliability data (Figure 1b), our approach provides up to 92% reduction in mean squared error, 7% increase in log-likelihood, and 61% decrease in maximum absolute error. On ring oscillator data obtained from laboratory experiments, the corresponding improvements are 94%, 5%, and 77%, respectively. For both simulated and real datasets, we validated the improvement in performance through statistical tests of significance. Finally, we apply our method to demonstrate an approach for empirical extraction of the temperature-dependence of parameters from lifetime data at different test temperatures.



▲Figure 1: (a) Mean squared error of DE vs L-BFGS-B across different sample sizes for a competing-risks model. (b) Single Weibull, mixture, and competing-risks model fits to Xilinx ball grid array failure data.

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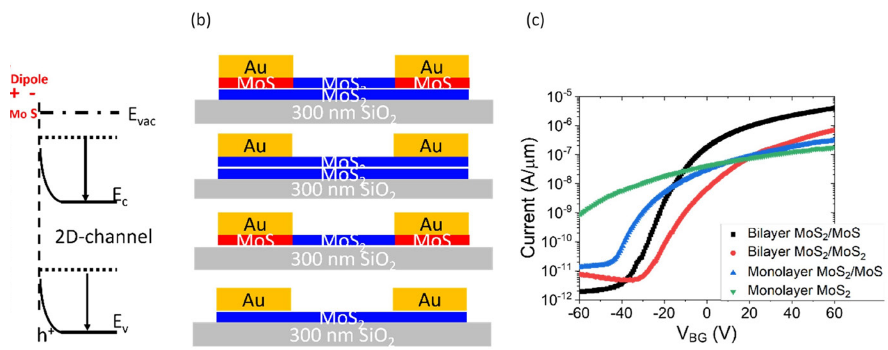
- U. Chakraborty, E. Bender, D. S. Boning, and C. V. Thompson, "Identification of Multiple Failure Mechanisms for Device Reliability Using Differential Evolution," *IEEE Transactions on Device and Materials Reliability,* vol. 23, no. 4, pp. 599-614, Dec. 2023.

Dipole-Engineered Contacts to Two-Dimensional Semiconductors

A. S. Gupta, J. Zhu, T. Palacios
Sponsorship: Army Research Office

Power transistors for fast-switching, high-voltage applications require wide bandgaps to enable large breakdown fields. Emerging ultrawide-bandgap (UWBG) two-dimensional (2D) semiconductors such as hexagonal boron nitride (hBN) and 2D gallium nitride (GaN) have bandgaps above 5 eV and are expected to provide better performance than current WBG semiconductors thanks to their higher critical fields and atomic thinness. However, forming low-resistance contacts to UWBG 2D materials is challenging due to their extreme energy band misalignment with conventional metal contacts and the Fermi level pinning effect, which both contribute to large Schottky barrier heights (SBHs).

Here, we propose using dipoles to reduce the SBH. Inserting a material with an appropriate built-in electric field at the contact interface will enhance carrier injection from the metal to the 2D channel (Figure 1a). In this work, we study contacts to MoS_2 with MoSSe, a so-called "Janus" 2D material, which has vertical asymmetry and therefore an inherent dipole. We demonstrate higher current density in Janus 2D material contacts than in conventional MoS_2 contacts to bilayer MoS_2 transistors, confirming the positive impact of dipole-tuned contacts. Future work will focus on contact materials with stronger dipoles, as well as wider bandgap channel materials such as hBN and 2D GaN. Overall, this work is a step towards forming ohmic contacts to WBG and UWBG 2D materials, thus enabling the next generation of power electronic devices with higher operation voltage as well as future integrated circuits with increased functionalities.



▲Figure 1: (a) Band diagram of dipole tuning effect, (b) schematics of back-gated MoS_2 transistors with and without dipole contacts, and (c) measured transfer curves of back-gated transistors.

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- J. Zhu, J.-H. Park, S. A. Vitale, W. Ge, G. S. Jung, J. Wang, M. Mohamed, T. Zhang, et al., "Low-thermal-budget Synthesis of Monolayer Molybdenum Disulfide for Silicon Back-end-of-line Integration on a 200 mm Platform," *Nature Nanotechnology*, vol. 18, pp. 456-463, 2023.

Field-free Deterministic Switching of a Perpendicular Magnetic Anisotropy van der Waals Ferromagnet Above Room Temperature

S. N. Kajale, T. Nguyen, N. T. Hung, M. Li, D. Sarkar
Sponsorship: Nano-cybernetic Biotrek Group, NSF, Department of Energy Office of Science, Basic Energy Sciences

Two-dimensional (2D) van der Waals (vdW) magnetic materials are emerging as a cornerstone for the next generation of spintronic devices, which are pivotal for advancing high-density, energy-efficient memory and computational technologies. The unique properties of vdW materials, such as their atomic-scale thickness and ability to exfoliate into 2D layers, offer unprecedented opportunities for miniaturization and integration into electronic devices. Recent break-throughs in the synthesis and manipulation of these materials have demonstrated their potential in spintronic applications, particularly through the control of spin-orbit torque (SOT) in vdW ferromagnets. However, the development of spintronic devices that operate efficiently at room temperature and require no external magnetic fields for operation remains a significant challenge. The ability to control the magnetic state of vdW ferromagnets electrically, with no need for magnetic fields, is crucial for practical deployment of compact and thermally stable devices. This control is especially important for applications in environments where magnetic fields may interfere with other electronic components or device miniaturization is critical.

In this context, we report a novel approach for achieving field-free, deterministic, and non-volatile switching of a perpendicular magnetic anisotropy (PMA) vdW ferromagnet, specifically Fe_3GaTe_2, above room temperature (up to 320 K). Our method utilizes the unconventional out-of-plane anti-damping torque generated by an adjacent WTe_2 layer, as shown in Figure 1. This configuration not only facilitates the desired field-free magnetic switching but does so at a low current density of 2.23×10^6 A cm^{-2}, showcasing the practical viability of this approach. Our study exemplifies the efficacy of vdW heterostructures comprising 2D magnets and low-symmetry vdW materials for efficient, field-free control of PMA magnetic tunnel junctions. It provides an all-vdW solution for the next generation of scalable and energy-efficient spintronic devices that can meet the growing demands of big data and artificial intelligence hardware.

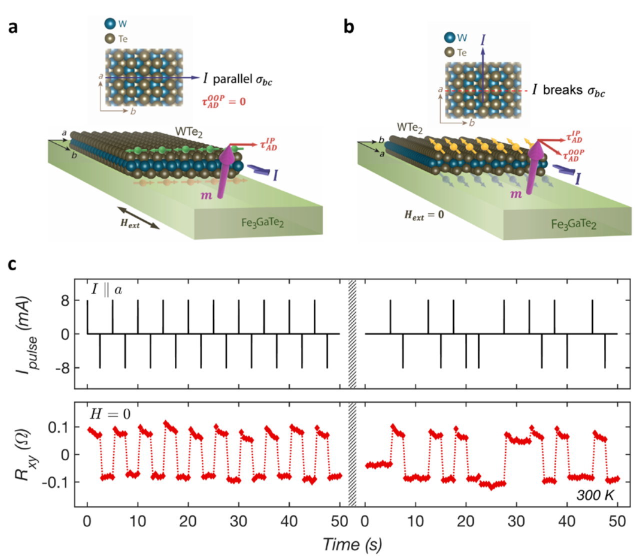

Figure 1: Schematic of Fe_3GaTe_2 device when current is applied along crystallographic (a) b-axis of WTe_2 and (b) a-axis of WTe_2. Out-of-plane anti-damping torque is generated only in latter case. (c) Field-free non-volatile switching of Fe_3GaTe_2 magnetization at 300 K using arbitrary train of current pulses.

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- S. N. Kajale, J. Hanna, K. Jang, and D. Sarkar, "Two-dimensional Magnetic Materials for Spintronic Applications," *Nano Research*, vol. 17, pp. 743–762, 2024.
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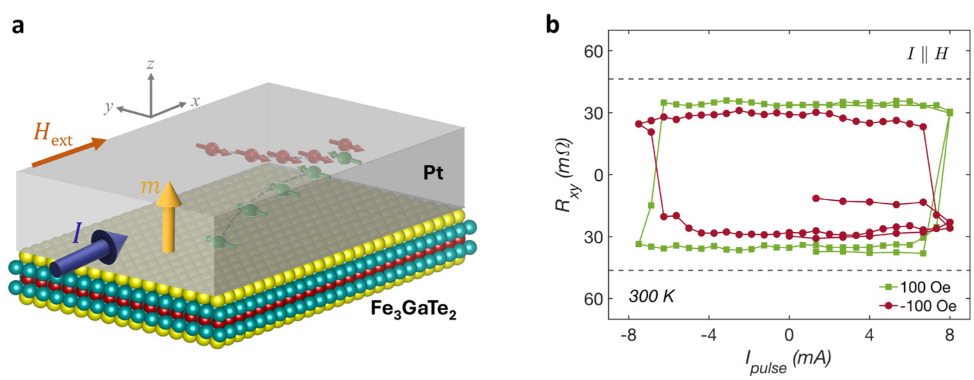
Room Temperature Spin-orbit Torque Switching of a van der Waals Ferromagnet

S. N. Kajale, T. Nguyen, M. Li, D. Sarkar
Sponsorship: Nano-cybernetic Biotrek Group

Recent discovery of emergent magnetism in two-dimensional van der Waals magnetic materials (vdWMM) has broadened the material space for developing spintronic devices for energy-efficient computation. Spintronic devices leverage the spin of electrons in addition to their charge to enable enhanced function-ality, high speeds, and lower energy consumption than in traditional charge-based devices. Spintronic devices are driving new paradigms of bio-inspired, energy efficient computation like neuromorphic stochastic computing and in-memory computing. While vdWMM discovery has progressed appreciably, a solution for non-volatile, deterministic switching of vdWMM at room temperature is missing, limiting the prospects of their adoption into commercial spintronic devices. Perpendicular magnetic anisotropy (PMA) magnets are crucial for scaling spintronic devices to advanced technology nodes, as they enable high thermal stability and efficient current-induced switching in nanoscale devices.

Here, we report current-controlled non-volatile, deterministic magnetization switching in a vdWMM, Fe_3GaTe_2, at room temperature. Fe_3GaTe_2 exhibits a high Curie temperature and strong perpendicular magnetic anisotropy, making it a promising candidate for spintronic applications. We have achieved spin-orbit torque (SOT) switching of Fe_3GaTe_2 using a Pt spin-Hall layer (Figure 1) up to 320 K, with a small threshold switching current density J_{sw} = 1.69 × 10^6 A cm^{-2} at room temperature, the lowest among all vdWMM-based SOT devices reported so far. We have also quantitatively estimated the anti-damping-like SOT efficiency of our Fe_3GaTe_2/Pt bilayer system to be ξDL = 0.093, using the second harmonic Hall voltage measurement technique. These results mark a crucial step in making vdWMM a viable choice for the development of scalable, energy-efficient spintronic devices for memory and logic components that can meet the growing demands of big data and artificial intelligence hardware.



▲Figure 1: (a) Schematic illustration of the Fe_3GaTe_2/Pt bilayer devices. (b) Current induced switching of Fe_3GaTe_2 magnetization, measured through anomalous Hall resistance (R_{xy}), at 300 K with in-plane magnetic field applied parallel to current.

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- S. N. Kajale, J. Hanna, K. Jang, and D. Sarkar, "Two-dimensional Magnetic Materials for Spintronic Applications," *Nano Research*, vol. 17, pp. 743–762, 2024.
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Highly Integrated Graphene-based Chemical Sensing Platform for Structural Monitoring Applications

C. Lopez Angeles, T. Palacios
Sponsorship: Ferrovial

Two-dimensional materials, such as graphene, hold promise for sensing applications. Graphene's remarkable surface-to-volume ratio, when employed as a transducer, enables the sensor channel to be readily modulated in response to chemical changes in proximity to its surface, effectively converting chemical signals into the electrical domain. However, their utilization has been constrained due to variations in device-to-device performance arising from synthesis and fabrication processes.

To address this challenge, we employ Graphene Field Effect Transistors (GFETs) in developing a robust and multiplexed chemical sensing array comprising tens of sensing units. This array is coupled with custom-designed high-speed readout electronics for structural monitoring applications, for example, detecting pH degradation in concrete.

In harsh environmental conditions, structures constructed from reinforced concrete may experience degradation due to corrosion, a chemical process initiated by carbonation and significant fluctuations in temperature and humidity. Under normal conditions, concrete maintains a pH level within the alkaline range of 13 to 14. However, when subjected to carbonation, its pH decreases to values between 8 and 9.

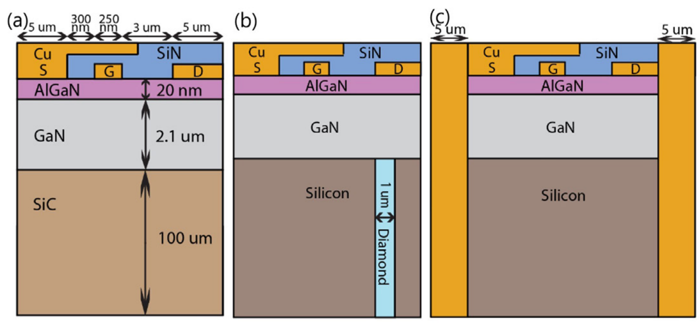
Our platform excels in real-time pH monitoring. By conducting I-V sweep measurements in the sensor channel, we have established a correlation between [H+] concentration and the gate-source voltage (VGS) at graphene's Dirac point with an accuracy of roughly 98%. This system and correlation allow for the prompt detection of any deviations induced by corrosion within a concrete environment.

Thermal Management in GaN High Electron Mobility Transistors (HEMTs)

D. Erus, T. Palacios

Wide bandgap of GaN make GaN HEMTs a key building block for the next generation of high-power and high-frequency electronics. However, the large power density in these devices induces harsh self-heating. GaN-on-Si structure enables the use of state-of-the-art fabrication tools which reduces defects and increases the yield. However, due to the lower thermal conductivity of Si compared to SiC, GaN-on-Si HEMTs have a higher peak temperature than the commonly used GaN-on-SiC HEMTs at the same power dissipation level.

In this work, the same Silvaco TCAD simulation framework is used to find thermal solutions that decrease the peak temperature of GaN-on-Si HEMTs. Making a 1 µm diamond via under the drain of the GaN-on-Si HEMT decreases its thermal resistance 38%. Covering the sides of the HEMT with Cu decreases its thermal resistance 70%, which is lower than the thermal resistance of the GaN-on-SiC HEMT. This work proposes a viable solution for thermal management in GaN-on-Si HEMTs.



▲ Figure 1: a) GaN-on-SiC HEMT structure; b) GaN-on-Si HEMT with 1 µm diamond via; c) GaN-on-Si HEMT with copper covered sides.

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Advanced Materials issues of GaN-on-Si Transistors for RF and Beyond

G. K. Micale, J. A. Perozek, Q. Xie, J. Niroula, H. Pal, P. Yadav, P. C. Shih, T. Palacios
Sponsorship: SRC Jump 2.0 SUPREME Center

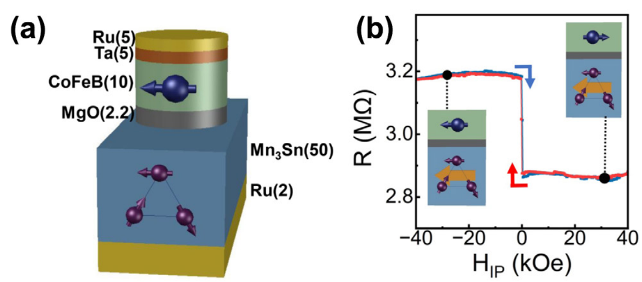
In an age of ever-increasing demand for high-speed communications, gallium nitride high-electron-mobility-transistors (GaN HEMTs) have emerged as a breakthrough technology to meet the frequency and power demands of modern electronics. Owing to their large breakdown voltages and high electron saturation velocity, GaN HEMTs are the leading technology for power and RF applications. Using Si substrates for GaN heteroepitaxy dramatically increases the cost-efficiency of GaN RF devices, but due to the lattice mismatch and low resistivity and thermal conductivity of Si substrates, GaN-on-Si device performance has lagged SiC, the leading substrate choice for high-frequency GaN devices. Achieving a deeper understanding of parasitics and their causes will enable major improvements to cutoff frequency (f_T) and maximum oscillation frequency (f_{max}) and offer helpful insights for fabricating more advanced device architectures.

Low resistance regrown ohmic contacts will help increase f_{max}. Combining reactive ion etching with novel wet etching techniques during contact fabrication is an effective way to control the sidewall angle and mitigate plasma damage in the recessed GaN, which will improve the regrown GaN/2DEG channel interface and reduce the contact resistance. In this work, we study two wet etching methods to use with inductively coupled plasma dry etching to optimize the interfaces of GaN recesses: (1) KOH and (2) a Digital Etch (DE) that alternates between H_2SO_4/H_2O_2 and dilute HCl. Comparing contact resistance from devices made with each method will help deconvolve the impact of plasma damage and sidewall angle on contact resistance. Furthermore, investigating the role of plasma damage, topology, and interface impurities on channel carrier density and contact resistivity that will facilitate ultralow resistance ohmic contacts that will play a key role in future high-power, high-frequency HEMT architectures.

Tunneling Magnetoresistance in Antiferromagnetic Tunneling Junctions

C.-T. Chou, B. C. McGoldrick, T. Nguyen, S. Ghosh, K. A. Mkhoyan, M. Li, L. Liu
Sponsorship: SRC, DARPA, NSF (DMR-210491, DMR-2011401), DOE (DE-SC002014), NNCI (CCS-2025124)

Achieving a high tunneling magnetoresistance (TMR) in junctions with antiferromagnetic (AFM) electrodes has been an enthusiastically pursued goal in spintronics, with the prospect of employing AFMs as next-generation memory and spin-logic devices. High TMR in antiferromagnetic tunnel junctions have been reported in the literature, but the underlying mechanism for the TMR is still not fully understood. In this work, we study Mn_3Sn/MgO/CoFeB tunnel junctions where AFM Mn_3Sn and FM CoFeB serve as fixed layer and free layer, respectively. Large TMR ratios up to 49% are observed in these junctions are comparable to that in conventional FM tunnel junctions. The large TMR suggests the effective spin polarization in AFMs can be as large as that in FMs when proper tunneling barrier and counter FM electrode are selected. The new physical mechanisms revealed by our results are critical for understanding spin polarized tunneling in AFM tunnel junctions.



▲Figure 1: (a) Schematic of the antiferromagnetic tunnel junction structure and (b) tunneling magnetoresistance at 10K. Inset: schematics of magnetic moments of the CoFeB and Mn_3Sn layers.

Atomically-thin Ferroelectric Transistors made from Rhombohedral-stacked MoS_2

T. H. Yang, Y. W. Lan, J. Kong
Sponsorship: U. S. Army Research Laboratory, U. S. Army Research Office (W911NF2320057)

Ferroelectric transistors are a promising technology to develop low-power and non-volatile computing-in-memory devices for neuromorphic machine learning architectures that overcome the von Neumann bottleneck. These devices require scaled thickness and ferroelectric channel materials. Two-dimensional high-mobility semiconductors such as molybdenum disulfide (MoS_2) are promising candidates for ultrathin ferroelectric channels due to their sliding ferroelectricity property. However, the realization of switchable electric polarization in epitaxial MoS_2 remains challenging, owing to the absence of mobile domain boundaries, thereby limiting aggressive translation into practical applications. Here, we explore polarity-switchable epitaxial rhombohedral (3R)-stacked MoS_2 as a ferroelectric channel for 2D ferroelectric memory transistors. We find that a shear transformation spontaneously occurs in our 3R-MoS_2 epilayers, producing heterostructures with stable ferroelectric domains embedded in a highly dislocated and unstable non-ferroelectric matrix. This diffusionless phase-transformation process produces mobile screw dislocations that enable collective polarity control of 3R-MoS_2 via an electric field. The polarization-electric field measurement reveals a switching field of 0.036 V nm^{-1} for shear-transformed 3R MoS_2. Individual 'sliding' ferroelectric transistors made of shear-transformed 3R MoS_2 are non-volatile memory units with only two atomic-layer-thickness, exhibiting an average memory window of ~7 V with an applied voltage of 10 V, retention > 10^4 s, and endurance > 10^4 cycles. Our work proves the potential of sliding-ferroelectricity-based transistors in the future ultra-scaled ferroelectric memory-transistor paradigm and provides a straightforward growth strategy for high-throughput manufacturing.

Compact Multi-terminal Nano-electromechanical Relay

T. Dang, J. Han, V. Bulović, J. H. Lang
Sponsorship: Analog Devices Graduate Fellowship

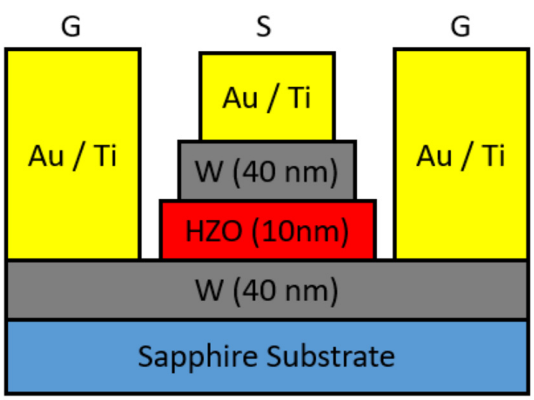
Nano-electromechanical (NEM) relays have emerged as promising candidates for complementing CMOS technology because of their superior characteristics, including zero leakage, steep sub-threshold slope, high on-off current ratio, and robustness in harsh environments. However, current implementations of NEM relays typically require intricate fabrication and large device active area due to their complicated design and structure, which brings significant challenges for their scaling, versatility, and monolithic integration with CMOS circuits. Therefore, a multi-terminal NEM relay with a simple structure, lateral layout, compact design, ease of processing, and high performance would be greatly beneficial. In this work, a nanoscale multi-terminal electromechanical relay with compact and simple device structures is fabricated with a single lift-off process, thereby allowing versatile implementations for ultra-low-power digital logic. The relay can achieve bistable switching behavior using a pair of gate/drain electrodes, as well as sub-1V actuation voltage with a pre-biased gate electrode, making it advantageous for use in energy-efficient and radiation-hardened electromechanical computing and storage. The lateral design is favorable for further scaling and is compatible with monolithic 3D integration to enable reconfigurable CMOS-NEM hybrid circuits. Together, these features enable the relay to perform as a key component for zero-standby-power electromechanical computing/storage and CMOS-NEM integration.

Temperature-dependent Impedance Characterization of Ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ Thin Films

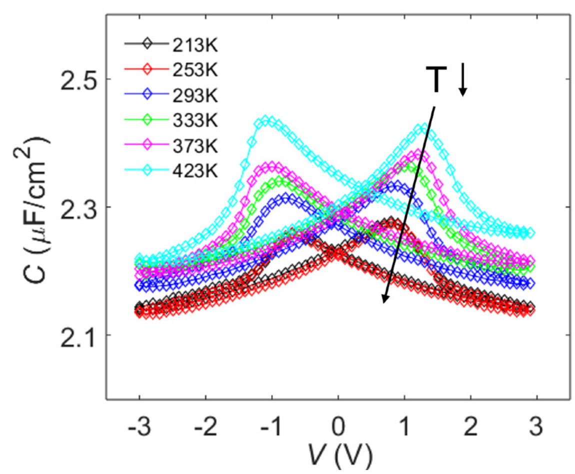
J. C.-C. Huang, Y. Shao, T. Kim, E. Borujeny, D. A. Antoniadis, J. A. del Alamo
Sponsorship: SRC, Ericsson

Since the discovery of ferroelectricity in Si-doped HfO_2, HfO_2 has become an attractive ferroelectric material due to its complementary metal-oxide semiconductor-compatibility and its potential applications in a variety of electronic devices such as ferroelectric (FE) field-effect transistor and analog non-volatile resistors. While various dopants have been introduced to induce ferroelectricity in HfO_2 films, $Hf_{0.5}Zr_{0.5}O_2$ (HZO) stands out because of its thickness scalability and outstanding ferroelectric properties. Though impedance measurements constitute a powerful method to investigate electrostatics and defect physics in microelectronics, it remains an underexploited technique when it comes to providing insight into FE properties of HZO. Our group has recently demonstrated impedance characterization of metal/FE/metal structures (MFM) over a broad frequency range up to 10 GHz and shed light on the role of defects in the dynamics of these structures.

In this work, we have performed temperature-dependent impedance characterization using coplanar waveguide devices consisting of W/HZO/W capacitors. These measurements cover a frequency range from kilohertz to gigahertz and a temperature range from -60 to 150°C. The results indicate that lower temperature and higher frequency might suppress electron hopping related to defects. We also find the convergence of capacitance-voltage peaks towards 0 volts while lowering the temperature, which has not been reported in the literature. Our findings can provide valuable insights into the underlying physical mechanisms governing FE switching in HZO.



◀ Figure 1: Schematic diagram of a W/HZO/W coplanar waveguide device.



▶ Figure 2: Capacitance-voltage curves of W/HZO/W structures measured at 1.9 GHz at various temperatures.

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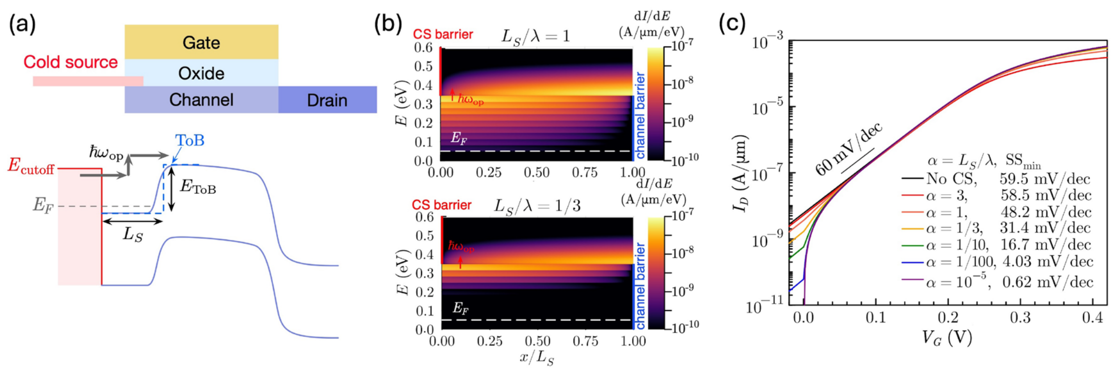
Simulation of Rethermalization Effect in 2D Cold-Source FET

P. Wu, S. A. Vitale, K. Tibbetts, J. Kong
Sponsorship: MIT Lincoln Laboratory Advanced Concept Committee

Transistors with steep subthreshold swing (SS) are of interest for reducing the supply voltage and thus the power consumption of integrated circuits. Cold-source field-effect transistor (CS-FET) has been proposed as a candidate for steep slope transistor, which relies on low-pass energy filtering from the cold source to enable cold carrier injection. However, previous studies on CS-FETs mainly focus on ballistic simulation, and the impact of scattering is often ignored. In this work, we develop a simulation framework based on the Boltzmann transport equation (BTE) that incorporates the impact of phonon scattering. Based on the simulation, we study the impact of the rethermalization effect on the off-state performance of CS-FET quantitatively and its dependence on device and material parameters. We find that the cold carriers will quickly rethermalize if the contact length between the cold source and the channel is comparable to the phonon-limited mean free path of electrons. Due to the small phonon-limited mean free path of MoS_2 (around 10 nm), it is unlikely to observe steep-slope switching in MoS_2-based CS-FET, in accordance with our previous experiment results. Finally, we apply the understanding from the simulation to provide a guideline of device design and material choice for experimental CS-FET implementation and point out the necessity of adopting a channel material with high mobility (or more precisely, long mean free path).



▲ Figure 1: Rethermalization in CS-FET. (a) Device schematics. (b) Simulated energy-position-resolved current spectrum for two different source overlap lengths LS. (c) Simulated transfer characteristics of different source overlap lengths L_S.

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- P. Wu, and J. Appenzeller, "Design Considerations for 2-D Dirac-Source FETs—Part II: Noni-dealities and Benchmarking," *IEEE Transactions on Electron Devices*, vol. 69, no. 8, pp. 4681-4685, Aug. 2022.

A Comprehensive Study on Si-ion Implanted Ohmic Contacts on AlGaN/GaN Heterostructure

M. Oh, Q. Xie, P.-C. Shih, M. Khoury, A. Kumar, R. Ley, B. D. Briggs, T. Palacios
Sponsorship: Advanced Research Projects Agency-Energy (ARPA-E) (grant no. DE-AR0001591)

Ohmic contacts to III-Nitride heterostructures pose challenges due to the wide band gap and the limitations of existing methods, e.g. low throughput for MBE regrown contacts, rough surface morphology for alloyed contacts, and the use of metal stacks that are incompatible with Si fabs. In contrast, implanted contacts offer ease of manufacturing with precise doping control and uniformity.

This work delves into Si-ion implanted ohmic contacts on AlGaN/GaN heterostructures. The contact resistance (R_C) of the implanted contacts can be divided in three components: R_{c1}, the resistance between the metal and the implanted region; R_{c2}, the resistance of the implanted region; and R_{c3}, the resistance between the implanted region and the two-dimensional electron gas (2DEG). R_{c1} reached a minimum when the ohmic metals were deposited after etching the entire AlGaN layer. R_{c2} is proportional to the length of the implanted region between the metals and 2DEG, thus can be reduced through precise lithography, such as electron beam lithography. R_{c3} was reduced by employing a dual-path implantation technique that increased the Si concentration at the interface between the implanted region and 2DEG. Both R_{c1} and R_{c2} had minimum values with a middle dose, indicating that a higher dose would lead to an increase in both carrier density and lattice damage, making the optimum value lie in the middle range.

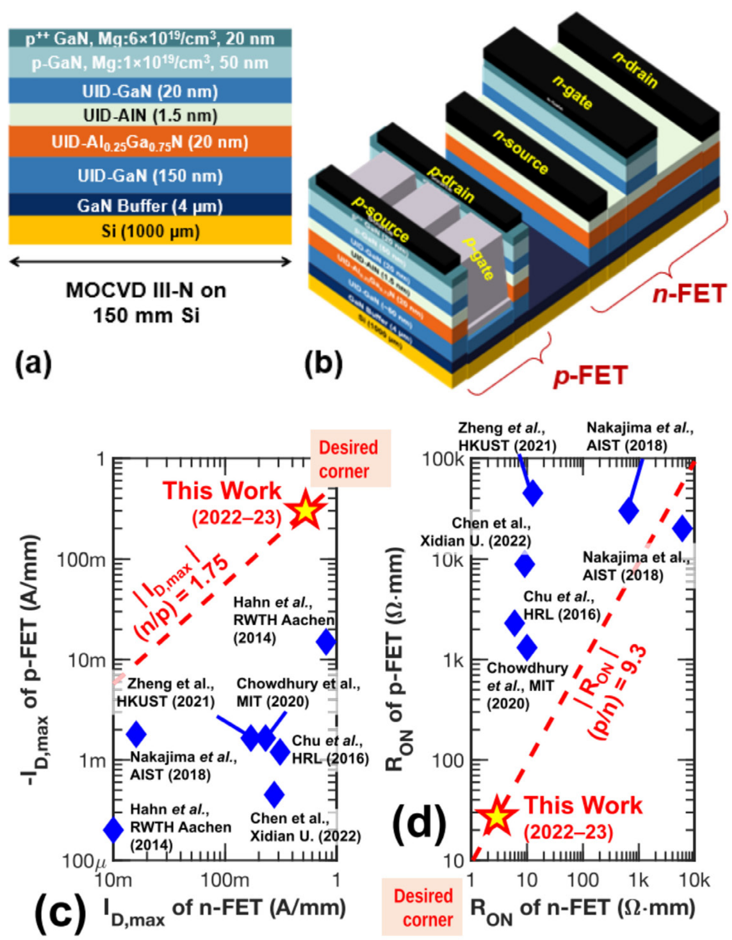
Moreover, this work explores, for the first time, high-temperature Si-ion implantation to form ohmic contacts on AlGaN/GaN heterostructures. Room temperature, 300 ˚C, and 500 ˚C were explored in this work, and XRD results demonstrated that less lattice damage was created by the implantation at high temperature. Electrical characterization showed that the higher the implant temperature, the more carriers were activated, resulting in lower R_{c1} and R_{c2} values. Consequently, the lowest Rc (average : 0.20 Ω·mm, minimum 0.14 Ω·mm) was obtained from 500 ˚C implantation with a dose of 3×10^{15} cm^{-2}.

Next-Generation High-Performance GaN Complementary Technology

P. K. Darmawi-Iskandar, Q. Xie, J. Niroula, T. Palacios
Sponsorship: Samsung Electronics Co., Ltd. (033517-00001), Qualcomm Inc. (MAS-492857), and National Defense Science, Engineering Graduate Fellowship

Gallium Nitride (GaN) complementary technology (CT) has the potential to offer record levels of efficiency, power, and compactness for data centers, power adapters, electric vehicles (EVs), and 5G/6G telecommunication systems. Over the years, significant research has been conducted on GaN-CMOS at MIT and worldwide, especially for high-voltage power management applications. However, the scaling limits of GaN CMOS for lower voltage applications have not been fully explored. Understanding the scaling limit of GaN is important for low voltage power management, mixed-signal IC, and RF amplifier applications.

This work seeks to explore the low voltage scaling limits of enhancement-mode n-channel p-GaN-gate HEMTs, through the combination of the following approaches: (1) material epitaxy, especially the polarization-inducing barrier; (2) novel transistor architecture to ensure good gate control at short channels; (3) improved processing to achieve aggressive scaling in these transistors.



▲ Figure 1: Highly scaled GaN complementary technology (CT). (a) Epitaxial structure. (b) Device structures of p-FET and n-FET based on the same GaN-on-Si platform as illustrated in Fig. 1(a). (c)(d) Benchmark of GaN CT transistors.

Materials - Synthesis & Characterization

AI-Empowered Automatic 2D Material Image Sampling and Scoring System

M.-C. Chen, A.-Y. Lu, S. Liu, J. Kong
Sponsorship: SRC JUMP 2.0 SUPREME Center

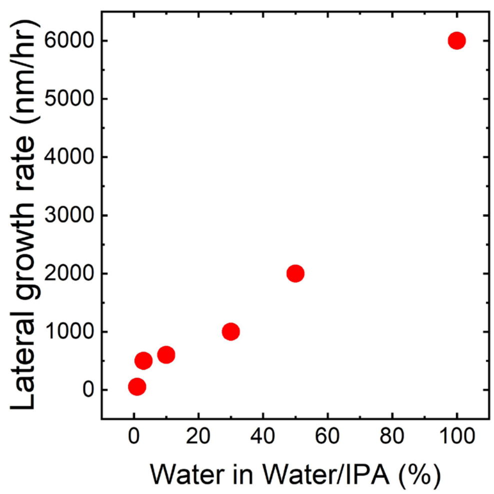
As the miniaturization of transistors progresses, the inherent physical limitations of silicon-based semiconductors, including leakage current, short-channel effect, and carrier mobility, are beginning to surface. Two-dimensional (2D) materials present a promising solution for further downsizing while preserving control over electronic properties. In the development of 2D materials, precise process control of chemical vapor deposition (CVD) is critical to the outcome, and our group has leveraged machine learning (ML) to expedite the process in several aspects, including literature text mining, recipe optimization, and unraveling correlation between Raman and photoluminescence spectra. For recipe optimization of our autonomous CVD synthesis platform, it is important to provide reliable feedback of CVD results to the recipe optimization algorithm. In this project, we aim to design an AI-empowered automatic 2D material image sampling and scoring system that can capture optical images of the 2D materials from CVD substrates, thereby avoiding human bias in selecting better crystals. The scope of this automated system starts at navigation of the linear motion stage to transferring the sample under the microscope, perform fine autofocus along the z-axis, taking images according to strategically designed sampling pattern and executing vignetting correction and stitching, all the way through image recognition with FastSAM, pattern statistics, and generating a final single score for each experimental result. Multiple independent functions including linear stage control, sample edge and angle detection, image processing, and FastSAM crystal recognition have been completed, and we are currently working on system integration. This system will enhance the integration of automatic characterization branch for our autonomous CVD platform and accelerate the further development of 2D materials.

Seeding Promoter Effect on Metal Organic Chemical Vapor Deposition Synthesized Molybdenum Disulfide

Y. Jiao, J. Zhu, T. Palacios
Sponsorship: Center for Heterogeneous Integration of Micro Electronic Systems (JUMP 2.0)

Two-dimensional (2D) transition metal dichalcogenide (TMD) materials are promising for next-generation electronics thanks to their excellent electronic and photonic properties. Metal organic chemical vapor deposition (MOCVD) has gained significant research interest for its excellent uniformity and quality. Many factors such as flow rate, temperature, and substrate conditions affect its growth quality. Optimization of the growth recipe is often difficult. Seeding promoters such as NaCl have been reported to significantly improve the growth rate and quality. However, a systematic understanding of the mechanism behind this improvement is yet to be quantitatively investigated. Understanding the effect of seeding promoters can benefit the optimization of growth recipes and lead to better uniformity of 2D material deposition process over large area substrates, which is one of the biggest limitations of the large-scale fabrication of 2D electronics.

Here, we quantitatively studied NaCl's promoting effect on the high temperature MOCVD growth of MoS_2. The study investigates the concentration dependence of the seeding density, flake size, and flake quality of as-grown MoS_2 and proposes the mechanism of NaCl's promoting effect. This study also discusses the trade-off and contamination issues of utilizing seeding promoters. With this result, we further optimized the growth and improved the material uniformity across the 200-mm platform as well as boosting the average mobility to around 50 $cm^2/(V \cdot s)$. This effort has provided insight into the fundamental growth mechanism and suggests a promising future of heterogeneous integration of TMD material and complementary metal-oxide semiconductor technology.



▲ Figure 1: Lateral growth rate change based on NaCl concentration in saturated water:isopropyl alcohol solution.

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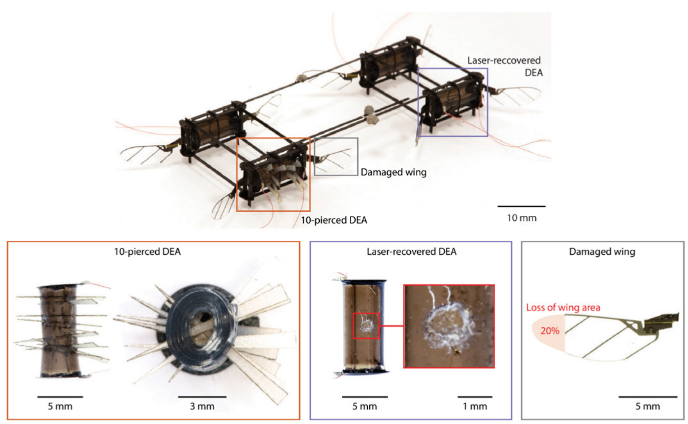
Laser-assisted Failure Recovery for Dielectric Elastomer Actuators in Aerial Robots

S. Kim, Y-H. Hsiao, Y. Lee, W. Zhu, Z. Ren, F. Niroui, Y. Chen
Sponsorship: NSF, MathWorks Fellowship

Dielectric elastomer actuators (DEAs) are a class of muscle-like soft actuators that are widely applied in many robotic systems demonstrating robustness against unexpected damage–a distinguishing feature that is challenging to achieved in robots with rigid actuators. However, unlike natural muscles, DEAs are prone to suffering local dielectric breakdowns. These often cause global device failure, limiting the performance, lifetime, and size scalability of DEA-based systems. Here, we developed an isolation process of defects or damages on DEAs (Figure 1) that directly cause local breakdowns. We first investigated the electromechanical evolution of external damage as the DEAs break down. Then, we designed a simplified material testing setup that can imitate piercing damages to optimize the fabrication of DEAs. Finally, we internally isolated the damaged area from original actuator structure. As a result, our DEAs can endure over 100 punctures while maintaining high bandwidth (>400 Hz) and power density (>700 W/kg) – sufficient for supporting energetically expensive locomotion such as flight.

Moreover, when the DEAs suffered severe dielectric breakdowns that cause device failure, we demonstrated a laser-assisted repair method for isolating the critical defects and recovering performance. We performed the ablation using diode-pumped solid-state laser that penetrates the transparent elastomer layer while partially degrading the electrode layer material. Then, we applied high voltage input to the actuator to electrically disconnect the ablated region from surrounding actuation area. We finally achieved 12-second controlled hovering flight with a 4-unit robot driven by pierced and laser-recovered DEAs along with the damaged wing (Figure 2). This laser-assisted repair technique demonstrates precise localization and isolation of critical defects, effectively decoupling actuator size from the probability of experiencing such defects. Consequently, our laser-assisted repair method enables the fabrication of considerably larger DEAs, thereby expanding the scope of applications across diverse domains. These findings culminate in the first aerial robot that can endure critical actuator and wing damage without compromising flight quality.

▲ Figure 1: A conceptual photograph illustrating a damaged biomimetic flying robot module that landed on a cactus.



▲ Figure 2: 760-mg flapping-wing micro aerial robot consisting of four modules that can endure severe piercing and burning damages on DEAs and having the tip of the wing cut off while maintaining controlled flight capability.

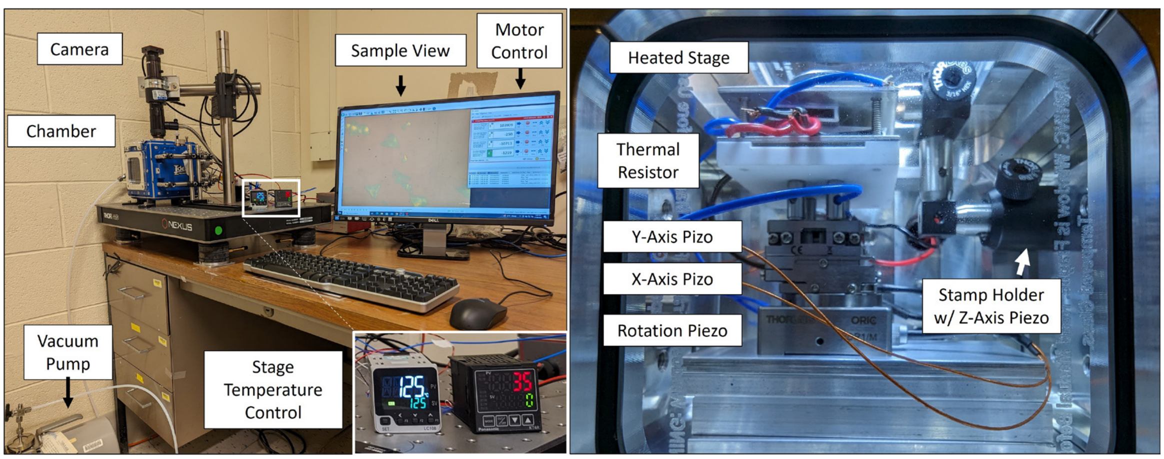
FURTHER READING

• S. Kim, Y-H. Hsiao, Y. Lee, W. Zhu, Z. Ren, F. Niroui, and Y. Chen. "Laser-assisted Failure Recovery for Dielectric Elastomer Actuators in Aerial Robots," *Science Robotics*, eadf4278, Mar. 2023.

Striving for Rapid Fabrication of Arbitrary, Ultraclean 2D Heterostructures using a Robotic Vacuum Transfer Setup and Automation

Z. Hennighausen, S. He, J. Wang, X. Zheng, T. Zhang, K. Zhang, K.Y. Ma, Z. Wang, J. Park, J. Kong
Sponsorship: US Army Research Office (grant number W911NF2210023), US Army Research Office through the Institute for Soldier Nanotechnologies at MIT (under cooperative agreement No. W911NF-18-2-0048).

Stacking two-dimensional (2D) materials into heterostructures facilitates the emergence of new properties, including superconductivity, interlayer excitons, and ferroelectricity, thereby enabling revolutionary new devices. Specialized transfer setups are required to fabricate 2D heterostructures with clean interfaces. Despite successes of the current technology, they require near-constant user engagement and a large time investment, thereby limiting throughput. To mitigate these challenges, we built a robotic transfer setup that operates in vacuum to reduce gas bubbles and improve interface cleanliness. We plan to identify ideal transfer parameters and fabricate 2D heterostructures with minimal user engagement using automation and machine learning. We plan to synergize the setup with materials grown in our group (e.g., graphene, hBN, TMDs, SnSe) and across MIT to fabricate increasingly complex heterostructures to advance technology in numerous areas (e.g., optics, electronics, qubits).



▲ Figure 1: Image of robotic vacuum transfer setup. (Right) Inside vacuum cube. Piezos enable x, y, z, and twist-angle control.

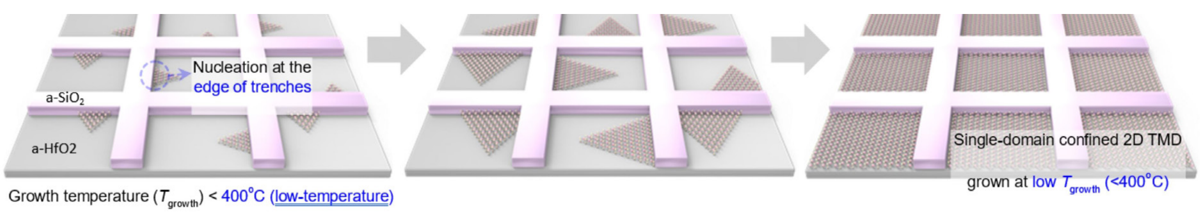
Non-epitaxial Growth of Single-crystalline Transition Metal Dichalcogenides at Low Temperature for Silicon Back-end-of-line Integration

D. Lee, K. Kim, S. Seo, J. Kim
Sponsorship: Samsung

Two-dimensional (2D) Transition Metal Dichalcogenides (TMDs) have been highlighted as a channel material for next generation electronics beyond Moore's law. However, their integration with conventional silicon technology has been a critical hurdle to commercialization because of their high growth temperature.

In addition, even though wafer scale growth of MoS_2 below the back-end-of-line (BEOL) temperature limit has been reported recently, its performance is not comparable to conventional silicon devices because the material is polycrystalline. Furthermore, WSe_2 growth below the BEOL limit has never been demonstrated, which is essential for the p-type devices needed to realize 2D CMOS circuits.

In this work, we overcome those challenges and demonstrate non-epitaxial single-crystalline growth of both MoS_2 and WSe_2 on an amorphous HfO_2 coated substrate below 400°C. We demonstrate that using our technique, their electrical performances are comparable to materials grown at high temperatures.

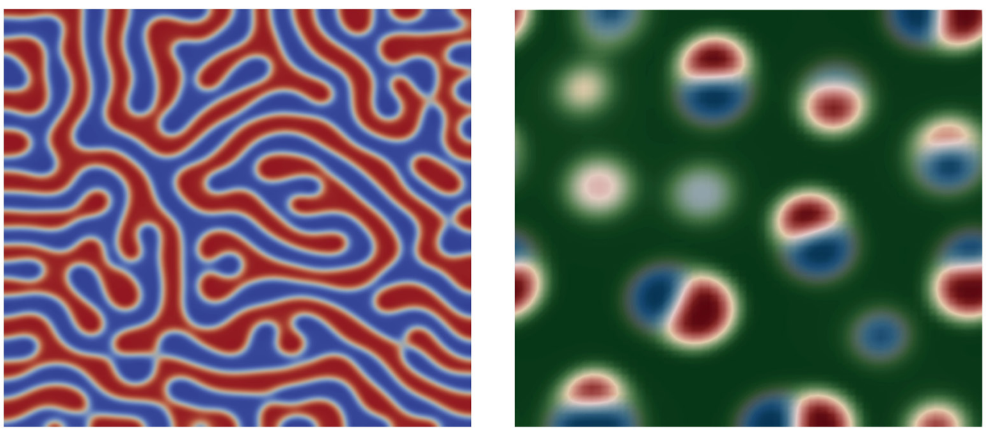


▲ Figure 1: The dangling bonds at the edge of SiO_2 trenches facilitate the nuclei formation even at low growth temperature. In addition, the trenches physically confine the extra lateral growth of single domain TMDs to prevent grain boundaries.

Continuum-Scale Modeling Strategies for Microstructure Formation and Evolution

P. K.Inguva, R.D. Braatz
Sponsorship: A*STAR

Understanding the formation and evolution of microstructures is of immense interest for engineering the properties and performance of advanced materials in a variety of applications. Phase-field models (PFMs) provide a convenient and extensible framework for studying multiphase and multi-component systems at length and time-scales otherwise inaccessible to meso- and molecular-scale methods such as molecular dynamics. PFMs introduce and track the evolution of one or more auxiliary variables (the phase field) whose values specify which phase is in each spatial location in the system at a given time. Depending on the application, PFMs can be solved by themselves or coupled to additional species, momentum, and energy conservation equations to suitably describe the physics of the process/system. The descriptive capabilities of PFMs have resulted in their widespread use in many areas of science and engineering including fluid dynamics, solidification, fracture mechanics, structure formation, and tumor growth modeling. The use of PFMs across multiple disciplines has resulted in relevant advances often being siloed, taking time to be disseminated across the literature. In this work, a framework for systematically conceptualizing PFMs (and their various extensions) is first outlined to inform their use and development. Subsequently, multiple case studies of increasing physical and computational complexity are presented to demonstrate the capabilities and limitations of using PFMs. All code for numerical simulations and additional details on the mathematics and physics of PFMs will be made available on a public GitHub repository. The developed resources will help accelerate the use of computational methods for developing advanced nanomaterials.



▲ Figure 1: Exemplar phase-field simulations of a binary (left) and ternary (right) polymer blends.

Mixed-dimensional Integration of 3D Complex-oxides on 2D Materials via Remote Epitaxy

J.-E. Ryu, S. Lee, K. S. Kim, X. Zhang, C. S. Chang, M.-K. Song, J. Kim
Sponsorship: IARPA (6948435)

A novel method for growing single crystalline three-dimensional (3D) complex-oxide layers on atomically thin graphene interlayer, known as remote epitaxy, has been proposed as the future of heterogeneous integration strategies. The technique enabled growth of high-quality thin film and perfect transfer of the grown film. However, However, the transfer of graphene, which is a typical process for forming a graphene interlayer on growth substrates, inevitably induces a significant number of unwanted defects such as wrinkles, holes, process residues, and interfacial contamination. Such defects can disturb the remote interaction between the substrate and epitaxial layer through graphene, reducing the crystal quality and exfoliation yield of membranes. Recently, we developed a direct synthesis method for growing alternative two-dimensional (2D) materials, such as transition metal dichalcogenides (TMDs), on growth substrates, which enables the creation of wafer-scale, defect-free 2D interlayers for reliable remote epitaxy of high-quality spinel $CoFe_2O_4$ (CFO) and garnet $Y_3Fe_5O_{12}$ (YIG) thin films. The atomically clean van der Waals interfaces formed by direct growth of TMDs onto growth substrates serve as an ideal platform for high-throughput production of single-crystalline, freestanding complex-oxide membranes that can be released from substrates, but also for facile fabrication of a new class of mixed-dimensional heterogeneous systems that exhibit emergent physical phenomena at well-defined 3D/2D heterointerfaces. Based on this unique approach to integrating mixed-dimensional heterostructures in a scalable and controlled manner, we demonstrate new device concepts that take advantage of unusual physical coupling or decoupling at exotic 3D/2D interfaces, which are both fundamentally intriguing and practically useful.

Controllable Vapor-phase Growth of Multilayer h-BN on Insulator

K. Zhang, Z. Hennighausen, H. Liu, J. Park, J. Kong
Sponsorship: U. S. Army Research Laboratory, U. S. Army Research Office (under contract/grant number W911NF2320057)

Multilayer hexagonal boron nitride (h-BN) is highly desirable as an ideal 2D insulator for the fabrication of two-dimensional (2D) van der Waals (vdW) heterostructures and superior electronic/ optoelectronic devices. However, achieving controllable synthesis of high-quality, large-area multilayer h-BN films, ranging from a few to dozens of layers, remains a challenge. Here, we employ a vapor-phase growth method to synthesize large-area multilayer h-BN films directly on insulator substrates (such as quartz or sapphire), using a Fe-Ni-B (Fe-B) alloy and nitrogen gas as precursors. The Fe-Ni-B alloy serves a dual purpose: it provides the boron source and catalyzes the reaction with nitrogen to form h-BN at a high temperature. Furthermore, we use an ice-assisted method to transfer the grown multilayer h-BN films onto arbitrary target substrates, thereby avoiding contamination from polymers or chemical agents. The outcome of the research efforts here will enable us to construct large-area, high-performance 2D functional heterostructures and devices.

Synthesis of Single-Crystal hBN Multilayers on Ni (111)

K. Y. Ma, Z. Hennighausen, J. Kong
Sponsorship: U.S. Army Research Laboratory, U.S. Army Research Office (contract/grant number W911NF2320057)

Two-dimensional hexagonal boron nitride (hBN) has been demonstrated to be the "ideal" dielectric substrate for 2D materials-based field effect transistors (FETs) – offering the potential for extending Moore's law using the superior electronic properties of these novel nanomaterials. Although hBN thicker than a monolayer is more desirable as substrate for 2D semiconductors, the growth of highly uniform and single-crystal few- or multi-layer hBN has not yet been demonstrated. Previously, K. Y. Ma et. al [1] developed the epitaxial growth of wafer-scale single-crystal tri-layer hBN by a chemical vapor deposition method. Uniformly aligned tri-layer hBN islands were found to grow on a 2 cm x 5 cm single-crystal Ni (111) at an early stage of growth and finally to coalesce into a single-crystal film. Cross-sectional transmission electron microscopy (TEM) results showed that a $Ni_{23}B_6$ interlayer is formed (during cooling) between the single-crystal tri-layer hBN film and Ni (111) substrate by boron dissolved in Ni (111) and that there is an epitaxial relationship between tri-layer hBN and $Ni_{23}B_6$ and between $Ni_{23}B_6$ and Ni (111). The tri-layer hBN film was found to act as a protective layer that remains intact during catalytic evolution of hydrogen – suggesting continuous and uniform single-crystal tri-layer hBN in large area. This tri-layer hBN was transferred onto the SiO_2 (300 nm)/Si wafer acting as a dielectric layer to reduce electron doping from the SiO_2 substrate in MoS_2 FETs. In this project, we will build upon the previous findings to achieve high-quality few-layer hBN for various applications.

FURTHER READING

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Amorphous 2D Materials – A Novel Platform for Remote Epitaxy and Nanopatterned Epitaxy of III-V Semiconductors with Low Decomposition Temperatures

K. Lu, N. M. Han, H. Kim, Y. Liu, S. H. Cho, J. Kim
Sponsorship: AFRL (FA9453-18-2-0017 and FA9453-21-C-0717), DARPA (029584-00001), DOE (DE-EE0008558), Umicore

Optoelectronic devices based on indium phosphide (InP), such as telecomm lasers, offer outstanding properties that outperform Silicon-based counterparts. However, the cost of InP wafers is considerably higher compared to commonly used semiconductor wafers. While reusing original wafers can effectively reduce costs, traditional techniques for wafer recycling, such as chemical lift-off, introduce significant expenses during fabrication, negating the cost savings achieved through wafer reuse. Consequently, the reuse of InP wafers becomes challenging but with significant opportunity, and new techniques are needed to scalably and cheaply produce InP membranes for optoelectronics.

Remote epitaxy and nanopatterned epitaxy have emerged as novel methods capable of facilitating the growth of InP with high quality, as well as enabling easy exfoliation of the InP films. These breakthroughs offer a promising avenue for cost-effective wafer reuse with the introduction of an interlayer of Two-dimensional (2D) materials between the epilayer and the substrate. Here we report the growth of amorphous boron nitride (a-BN) on InP wafers at low temperature that enabled improved quality of InP epitaxial membranes and their perfect exfoliation. We show fully covered a-BN on InP despite the low decomposition temperatures of InP substrates. The surface of a-BN coated InP substrate remains smooth with a RMS roughness of around 3 Å. We also demonstrate 100% coverage of single-crystal InP membranes grown on a-BN, with the film's quality remaining high. Through this low temperature molecular beam epitaxy (MBE) growth approach with remote epitaxy and nanopatterned epitaxy, we successfully demonstrate large-scale flexible InP membrane exfoliation and recycling of InP substrates, which will lead to new opportunities in InP membrane-based optoelectronics and novel heterostructures with significantly reduced cost.

Spike Timing Dependent Plasticity in Electrochemical Ionic Synapses

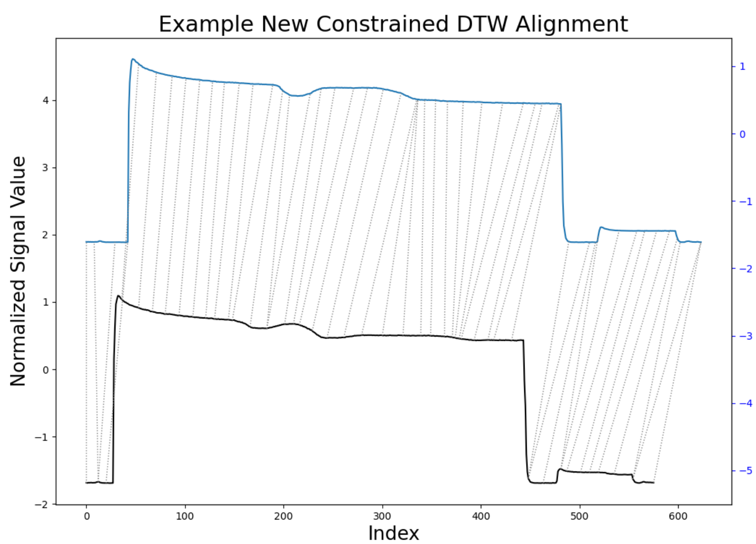
M. Huang, J. A. del Alamo, J. Li, B. Yildiz
Sponsorship: MIT Quest for Intelligence Program

Spiking neural networks (SNNs) have emerged as a promising architecture for machine intelligence due to their potential for highly efficient computation. However, realizing these networks in hardware presents unique challenges, particularly regarding the development of programmable synaptic devices capable of achieving time-dependent weight updates. Electrochemical ionic synapses (EIS) provide a promising solution, with their high energy efficiency, low variability, and rich ionic dynamics. In this work, we leverage the strong nonlinearity of EIS to implement various forms of spike-timing-dependent plasticity (STDP), a fundamental mechanism underlying learning in biological systems. Our results showcase STDP timescales ranging from milliseconds to nanoseconds, enabling high computing throughput. By designing appropriate pre- and post-synaptic neuron signals, we demonstrate that different forms of the STDP function can be deterministically predicted and emulated. Additionally, heterogeneous STDP within an array can be realized, where synapses from a single pre-neuron connecting to different post-synaptic neurons can exhibit distinct learning rules. Furthermore, we observe lower variability compared to existing hardware STDP implementations. Overall, our findings suggest that EIS could enable highly efficient SNN hardware implementations with high throughput. We believe this would further advance the development of bio-inspired computing and intelligent systems.

Dynamic Time Warping Constraints for Semiconductor Processing

R. Owens, F. Sun, C. Venditti, D. Blake, J. Dillon, D. S. Boning
Sponsorship: Analog Devices, Inc.

Semiconductor fabrication monitoring has become increasingly complex, and nonlinear variations in signal timing have made anomaly detection more difficult. We present a new method for preprocessing semiconductor sensor signals that improves anomaly detection model performance. The proposed method uses dynamic time warping (DTW) and semiconductor processing domain knowledge to address the problem of nonlinear signal alignment. New constraints for the DTW algorithm are developed based on semiconductor processing recipe steps. In tests using the kernel density estimation (KDE) fault detection method on labelled plasma etch datasets, the new constraints consistently outperform comparison methods. This demonstrates the usefulness of DTW, and specifically the new DTW constraints, as a preprocessing method for semiconductor sensor signals used in anomaly detection.

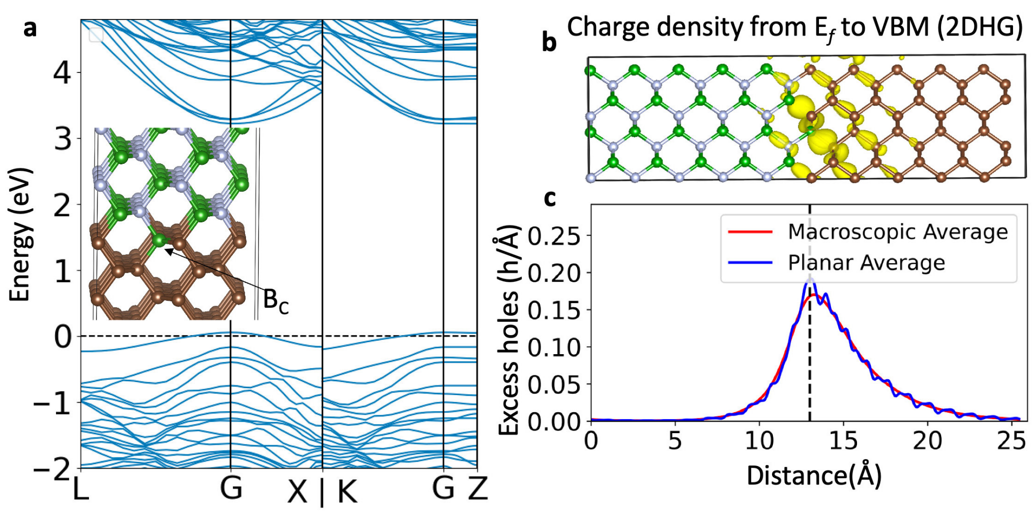


▲ Figure 1: Alignment of two optical endpoint signals. The grey dotted lines indicate mappings between the signals which were generated using the proposed constraints on the DTW algorithm.

Understanding the Role of Defects at Diamond/cBN Interface: A First-principles Study

S. Saini, K. J. Tibbetts, M. J. Polking, B. Yildiz
Sponsorship: MIT Lincoln Laboratory for Cubic BN/Diamond Heterostructures for High-Power RF Electronics

Diamond and cubic boron nitride (c-BN) stand out in high-power electronics due to their wide band-gap, and high thermal conductivity. Despite advancements in epitaxial c-BN growth on diamond, optimizing carrier mobility at the c-BN/diamond interface is impeded by a limited knowledge of the impacts of defects. Our first-principles study investigates the diamond/c-BN interface, focusing on crystal orientation, defects, and doping effects on electronic properties. We found that intrinsic defects, BC and CN, induce p-type doping and lead to 2D hole gas (2DHG) formation, BC case is shown in Fig.1. The electron-deficient nature of these defects and the type-II band alignment are crucial for 2DHG formation. Our work highlights the importance of defect engineering in enhancing the performance of diamond-based electronic devices.



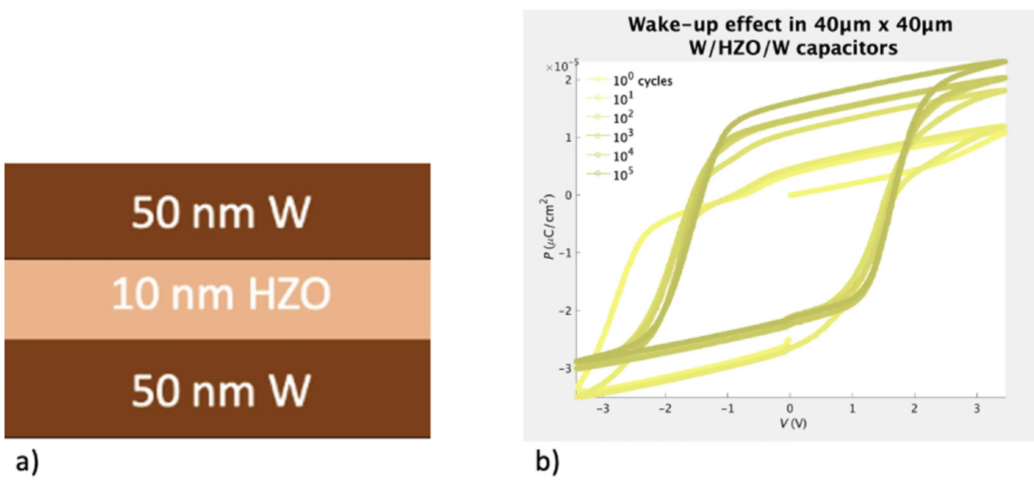
▲Figure 1: (a) Electronic band structure of BC defect at the diamond/c-BN(110) interface. (b) Charge density distribution, and (c) excess holes from Fermi level to valence band maximum.

Endurance Characterization of Ferroelectric Hafnium Zirconium Oxide for Memory Applications

T. E. Espedal, Y. Shao, E. R. Borujeny, J. A. del Alamo
Sponsorship: MIT UROP, Intel Corporation, Semiconductor Research Corporation

To realize on-chip next-generation AI accelerators, 3D monolithic integration of non-volatile memory (NVM) on CMOS is highly favored. Among different NVW technologies, ferroelectric (FE) memory based on CMOS-compatible hafnium zirconium oxide (HZO) has emerged as one of the most promising, as it could potentially provide low-voltage operation, fast switching, long data retention, and high device endurance. Understanding the detailed ferroelectric polarization switching physics in HZO thin films is of great importance for potential memory applications.

In working towards developing high-endurance back-end-of-line (BEOL) ferroelectric NVM technology, we investigate the endurance property of HZO in metal/FE/metal (MFM) structures that have been prepared with a variety of material stacks and fabrication parameters. We have studied unique physics in FE-HZO, including wake-up, fatigue, and breakdown, by carrying out repeated polarization-voltage measurements with carefully designed voltage pulse patterns. Through correlation with HZO fabrication parameters and materials characterization, we expect to better predict prospects and limitations of HZO in applications to future FE memory devices.



▲ Figure 1: a) Schematic diagram of W/HZO/W structure: 50 nm W / 10 nm HZO / 10 nm W b) Evolution of polarization-voltage (P-V) loop with increasing numbers of switching pulses applied.

Formation of Monolayer Metal Oxides via Room Temperature Conversion of Two-Dimensional Transitional Metal Dichalcogenides

X. Zheng, P. Wu, A. Penn, Z. Wang, T. Zhang, X. Zhong, J. Wang, J. Park, S. Xie, A. Kahn, D. Schlom, J. Kong
Sponsorship: SRC

Two-dimensional (2D) materials have attracted significant interest due to their ultra-thin thickness and quantum confinement effect. Despite the rich and diverse library of discovered 2D materials, the investigation on 2D oxides has been limited. There is a demand for atomically thin oxides because their band gaps are usually in the range of 3-6 eV, a range less accessible using the most studied 2D materials, such as graphene, transitional metal dichalcogenides (TMDCs) or h-BN. Here, by using 2D TMDCs as templates and converting them to oxide, we show that wafer-scale amorphous oxides can be directly formed at room temperature. The oxidation is enabled by UV light-generated ozone, which is a mild, controllable and homogeneous process. The properties of the as-converted transitional metal oxide monolayers are explored using optical, electrical and electron microscopic approaches. We further explored the potential applications of molybdenum oxide monolayers in two-dimensional field effect transistors. This strategy can be easily extended to a variety of metal oxides, enabling future development of metal oxides in the quantum regime.

Low Temperature Wafer-scale Synthesis of 2D TMD Material for Back-end-of-line Heterogeneous Integration

Y. Jiao, J. Zhu, T. Palacios
Sponsorship: Center for Heterogeneous Integration of Micro Electronic Systems (JUMP 2.0)

Two-dimensional (2D) transition metal dichalcogenide (TMD) materials have demonstrated promising future in the next generation of highly scaled microelectronic devices for their excellent electronic and photonic properties such as high mobility, direct bandgap in combination with their atomic scale dimensions. These properties have also made 2D TMD materials ideal candidate for back-end-of-line (BEOL) integration process with silicon front-end integrated circuits (IC). However, the current method of transfer integration of 2D TMD material and Si IC potentially introduces damages and defects to the material, thus greatly impedes the performance of fabricated devices. Direct growth of TMD was proven difficult in BEOL process due to temperature limits (<400°C)

In this work, we explore the low temperature large wafer-scale direct synthesis of high quality 2D TMD (MoS_2, $MoTe_2$, WSe_2, etc.) which are BEOL compatible. The Metal-Organic Chemical Vapor Deposition (MOCVD) system we designed is capable of direct growth on platforms up to 200 mm in diameter. The BEOL compatibility is achieved through separation of high temperature precursor decomposition region and low temperature deposition region. This enables monolayer TMD materials direct integration with Si front end devices without introducing damage, thus maintaining the optimal device performance. This integration technique shall bring a promising future of heterogeneous integration of TMD with various front-end substrates and applications in flexible electronics, optoelectronics and other monolithic 3D integration electronics.

High Indium Content InGaN Strain Relaxation

Y. Liu, B. Park, J. Kim, J. Kim
Sponsorship: Samsung

Light-emitting diodes (LEDs) are widely used in illumination and displays because of their high efficiency and brightness. Indium gallium nitride (InGaN) has been used as the material to make blue and green LEDs due to its tunable bandgap. However, in order to decrease the band gap of InGaN, more indium has to be incorporated into the material, leading to a high lattice mismatch between the InGaN layer and the GaN substrate. This mismatch decreases the quality of high indium content InGaN, which is an obstacle to the effective use of InGaN as the base material for RGB (red, green and blue) pixels. Here, we propose a method to fabricate high quality LEDs based on InGaN with high indium content using remote epitaxy. Conventionally, when an epilayer is grown on the substrate using epitaxial methods, the lattice structure of the epilayer always perfectly follows the lattice structure of the substrate by forming a covalent bond. Remote epitaxy, on the other hand, provides a way to copy the substrate lattice structure to a freestanding, non-covalently bonded thin film epilayer. When a layer of 2D material is deposited prior to the epilayer, the epilayer grown on the top of the 2D material still follows the crystalline structure of the substrate under the influence of the penetrated potential field from the substrate. However, unlike normal epitaxial methods, the epilayer spontaneously relaxes due to the slippery surface of the 2D material, attached by van der Waals forces rather than covalent bonding. Therefore, high quality InGaN can be obtained with this method. We demonstrate remote epitaxy of high-quality InGaN epilayers based on in-situ MBE-grown amorphous boron nitride (a-BN) as the release layer. By depositing InGaN on a-BN/GaN substrate, the misfit strain can be relaxed from the beginning of the growth regardless of the indium composition, enabling high-quality RGB LED pixels that can be used in superior electronic device displays.

Electric Field-induced Rapid Growth of Single-Crystal Graphene

Z. Wang, J. Wang, Z. B. Hennighausen, S. Y. Jeong, J. Kong
Sponsorship: The Semiconductor Research Corporation Center 7 in JUMP 2.0 (award no. 145105-21913)

Chemical vapor deposition (CVD) has emerged as an effective method for the synthesis of high-quality and large area graphene. However, achieving rapid synthesis of high-quality, single-crystal graphene remains a challenge. Recent studies have shown that the synthesis of single-crystal, high-quality graphene is achievable utilizing 500 nm - 700 nm single-crystal Cu(111) film on sapphire as catalyst and substrate. Nevertheless, the severe evaporation of the thin copper film during high-temperature growth has always been an issue. It has been reported that applying electric field between the copper substrate and a counter electrode could accelerate graphene growth, which can significantly shorten the duration of exposure of thin Cu(111) film to high temperature. In our study, we combined these two methods to use their respective advantages for the rapid synthesis of single-crystal, high-quality graphene. We applied electric field to both low pressure and ambient pressure chemical vapor deposition of graphene, while using single-crystal Cu(111) film on sapphire as the catalyst and substrate. We aim to shorten the growth time for low pressure CVD to within five minutes, and for ambient pressure CVD to within thirty minutes, for growing complete single-crystal graphene film on Cu(111). We believe that this integrated method holds promise for enhancing the efficiency and accessibility of high-quality graphene synthesis.

Medical Devices & Biotechnology

Ingestible Electronics for High Quality Gastric Neural Recordings

A. Gierlach, S. S. You, P. Schmidt, G. Selsing, I. Moon, K. Ishida, J. Jenkins, W. Abdalla M. Madani, S-Y. Yang, H-W. Huang, S. Owyang, A. Hayward, A. P. Chandrakasan, G. Traverso

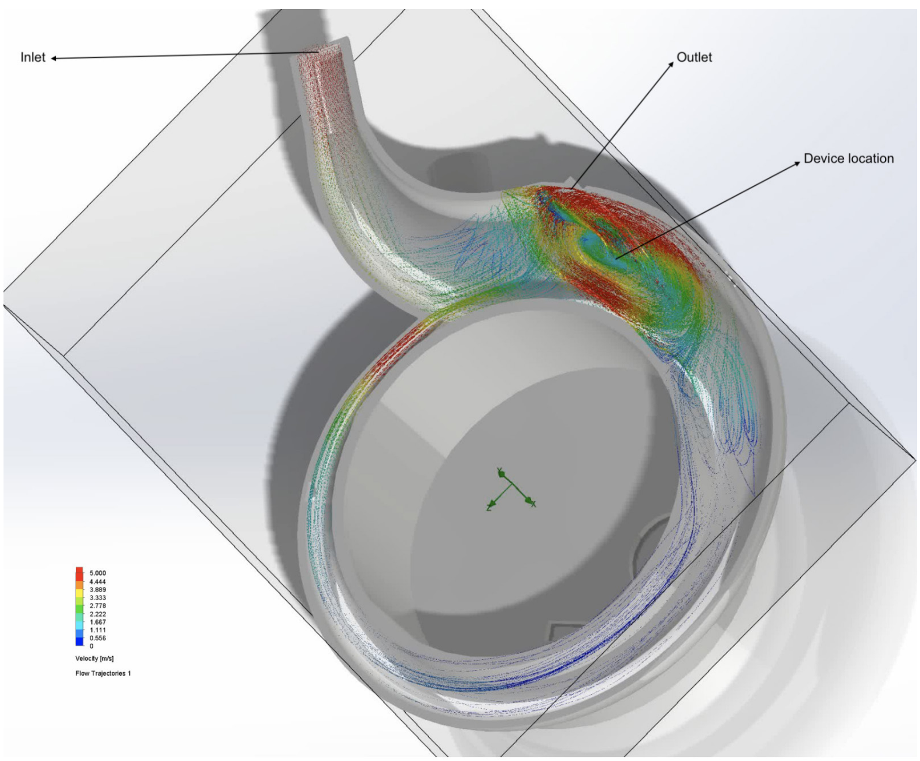
Recent advances in understanding gastrointestinal dysmotility, the gut-brain axis, and gastric stimulation therapies have highlighted the importance of the electrical signals that regulate the gastrointestinal (GI) tract. However, current tools that can measure these small, slowly oscillating potentials deep within the GI tract either involve acute, invasive procedures for high quality measurements or long-term cutaneous recordings that are highly attenuated and restrict patient movement. Here we introduce a non-invasive system for long term gastric recordings known as Multimodal Electrophysiology via Ingestible Gastric Untethered Tracking (MiGUT). Validated using the gold standard, MiGUT is able to record the gastric slow wave in-vivo in pigs, measure the expected response of prokinetic agents, while also directly observing signals from nearby organs such as the heart rate and respiratory rate. During multi-day measurements of freely-moving subjects, MiGUT measured changes in the slow wave during different behaviors and was not impacted by ingestion or high activity events. This work demonstrates new capabilities of ingestible devices, enabling long-term, at home, personalized diagnostics and detailed study of gastric electrophysiology algorithms.

Chamber Design and Airflow Optimization for E-nose Technology

M. Grande, C. Lopez Angeles, T. Palacios
Sponsorship: Universidad Politecnica de Madrid

Electronic nose (E-nose) technology has been explored for years. However, it has not yet achieved the digitization of the sense of smell with high accuracy. Various concepts of E-nose have been proposed, such as individual semiconductor-based sensors that respond to a certain chemical stimulus. However, their use has been limited due to variability on device-to-device performance resulting from nanofabrication processing. Moreover, when it comes to complex environments, such as the human breath, that involve many gases in low concentrations, a more robust and accurate sensing approach is needed. In this context, we are designing an E-nose system based on multiple graphene field-effect transistor (GFET) sensors arranged in an array. Each sensor chip is equipped with a thousand sensing units, aiming for enhanced precision in measurements.

These sensors, integrated with a printed circuit board system and an external computer, will enable the detection of biomarkers in exhaled breath. So far, we have achieved a good chemiresistive response of a metal nanoparticle functionalized graphene sensor to 10,000 ppm H_2, 100 ppm NH_3, 10 ppm H_2S, and 100 ppm NO_2 in dry air at room temperature. To optimize the performance, these devices are housed in a chamber design and engineered to ensure efficient airflow for detection. Furthermore, finite element modeling and simulations of airflow were utilized to enhance sensing module performance. This optimization was found through air recirculation and maximization of air volume in contact with the device. We found that chip performance is enhanced by creating localized vortices in the sample chamber. The air samples can be obtained either by exhaling into the chamber or by activating a vacuum extraction pump to capture ambient air. This research represents a significant step toward achieving a practical E-nose system for diverse applications, including disease diagnosis.



◀ Figure 1: SolidWorks simulation showing breath velocity trajectories. Breath vortices are shown specifically localized to enhance device performance and air profiles contact. Main vortex localizes where chip is placed; device design recirculates air.

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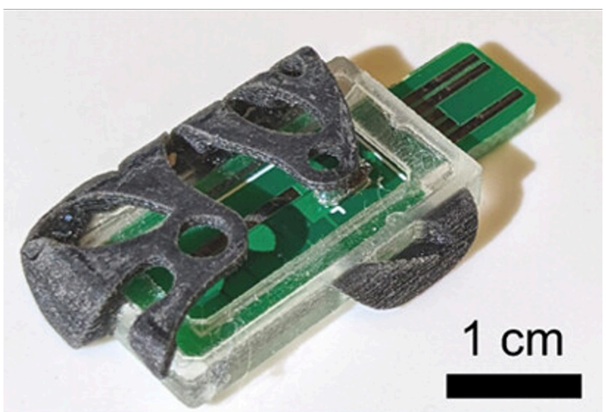
Additively Manufactured Electrospray Sources for Point-of-Care Mass Spectrometry

A. Kachkine, L. F. Velásquez-García
Sponsorship: Empiriko Corporation

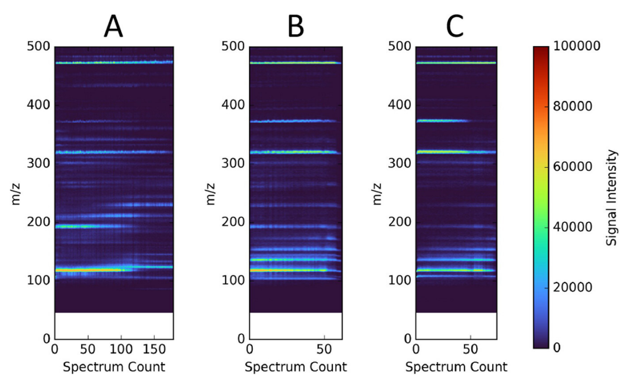
Clinical mass spectrometry of biological liquids, e.g., serum, allows fast and sensitive analysis of biological analytes. Mass spectrometry (MS) has yet to reach its full clinical potential. In particular, MS applications have been hindered by difficulties in constructing robust sample processing and ionization workflows, with existing methods requiring significant manual intervention.

Ionization of liquids is commonly attained via electrospray. The morphology of an electrospray emitter influences its performance. Internally fed emitters, i.e., capillaries, suffer from a variety of issues ranging from clogging to difficulty of integration; cleanroom microfabricated versions are expensive and time-consuming to make. Unfortunately, low-cost electrospray ionizers, e.g., paper spray, are often difficult to integrate into MS protocols.

This study focuses on the ionization step in standard MS protocols, concentrating on combining mainstream 3D printing technology and nanostructured surface treatments to achieve scalable manufacturing of high-precision hardware with automatable assembly. Each device comprises a digital microfluidic PCB, a soldered 3D-printed emitter made of SS 316L via binder jetting, covered by a conformal layer of hydrothermal ZnO nanowires, and an external 3D-printed casing (Figure 1). Using the 3D-printed ionizer, it was possible to detect pharmaceutical relevant compounds spiked in serum at a concentration of 1 μg/ml using various sol-vents (Figure 2).



▲Figure 1: A 3D-printed ionizer for point-of-care MS.



▲Figure 2: Time-series MS data from a 3D-printed ionizer using A) isopropanol, B) methanol, and C) acetonitrile as solvent. The sample included lisinopril, enalapril, clopidogrel, nicardipine, apixaban, atorvastatin, rosuvastatin, pravastatin, aspirin, and rivaroxaban.

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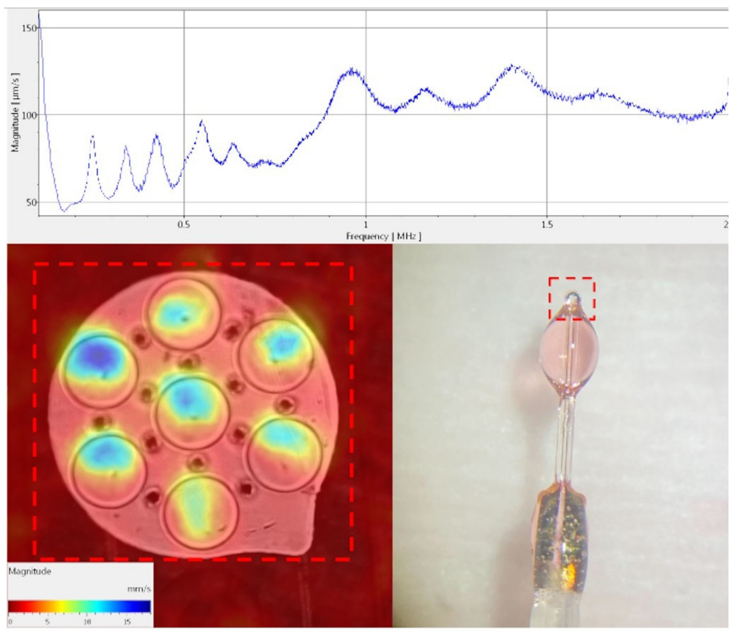
An Implantable Device for In-situ Ultrasound-enhanced Drug Delivery

J. F. Hou, S. B. Ornellas, M. O. G. Nayeem, C. Dagdeviren
Sponsorship: Media Lab Consortium Funding

Current intratumoral drug delivery strategies enable delivery of mRNA therapeutics but have poor tissue specificity and a need for repeated doses. Microfluidic devices enable targeted and controlled drug delivery, and ultrasonic cavitation has been used to reversibly modulate the permeability of tissue. A combined effect allows delivery of a drug payload to our target and enhanced penetration with an array of ultrasound transducers.

In this work, we create a novel piezoelectric Micromachined Ultrasonic Transducer (pMUT) with a microfluidic channel for in-situ drug delivery. Our device is based on an array of lead-free potassium sodium niobate (KNN) thin films and is transfer-printed on a flexible SU-8 substrate. The biostable nature of our devices enables chronic and responsive delivery for the treatment of intracranial tumors, and our results highlight the microfabrication and early characterization of the device performance in-vitro.

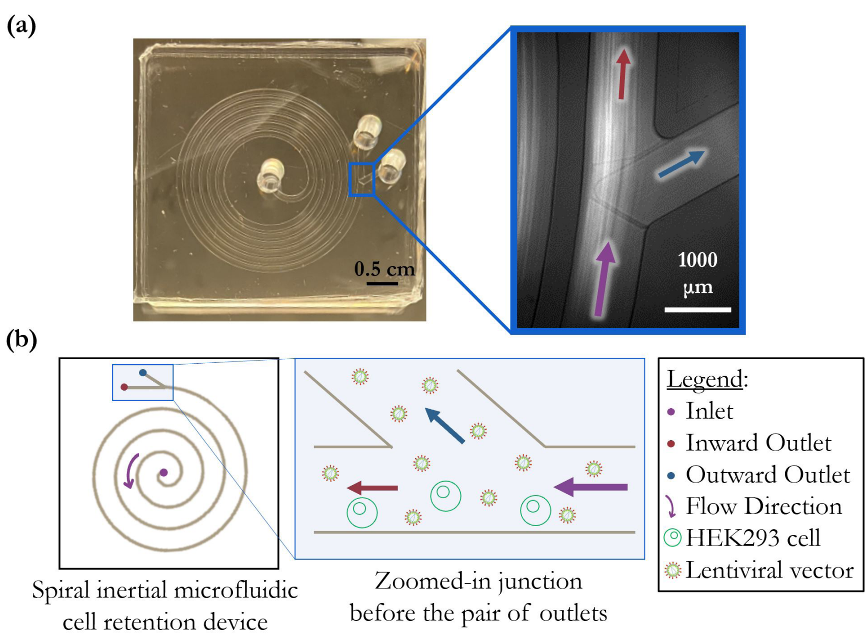


▲Figure 1: Laser doppler vibrometer measurement of average velocity of transducer at various frequencies (top), Relative magnitude of velocity over the array (bottom left), Full scale device with water injected through the microfluidic channel (bottom right)

Continuous Lentiviral Vector Harvesting from HEK 293 Perfusion Culture using Spiral Inertial Microfluidic Technology

A. Bevacqua, F. Liu, D. H. Park, J. Chen, J. Han
Sponsorship: Food and Drug Administration (1R01FD007480-03) and NSF Graduate Research Fellowship

Lentiviral vectors are popular gene delivery tools used to create gene and cell therapies. With these therapies costing patients over $400,000 per dose, research to develop high-concentration, high-yield viral vector manufacturing strategies has a pivotal role in advancing therapy commercialization efforts and lowering costs. Viral vectors are manufactured in HEK 293 cell perfusion culture and a cell retention device is used to separate viral vectors from cells. Many membrane-based cell retention devices used in industry struggle to maintain high product recovery over long production runs. We used a spiral inertial microfluidic cell retention device to carry out high-recovery harvesting from perfusion culture. We achieved 7 days of continuous lentiviral vector production and harvesting with a peak, unconcentrated, functional titer of 10^8 transducing units/mL, with a high recovery throughout production. Advancing viral vector harvesting strategies will expand treatment accessibility.



▲Figure 1: (a) The spiral inertial microfluidic device inertially focuses cells to the spiral's inward outlet (red arrow). (b) Viral vectors are continuously harvested through the outward outlet (blue arrow), since their motion is unbiased by inertial focusing.

Tracking Neurocognitive Decline via Abnormalities in Eye Movements Recorded on Mobile Devices

J. Koerner, V. Sze, C. G. Sodini, T. Heldt
Sponsorship: Aging Brain Initiative

The aging brain inevitably manifests in a decline of mental abilities. However, it is often difficult to discern age-related decline in neurocognitive performance from a decline due to neurodegenerative disease processes, especially early in the disease process when disease-modifying interventions are thought to be most effective. To this end, certain features of eye movements have been shown to be sensitive and specific markers of neurodegenerative disease progression. However, their quantitative measurements and assessments have hereto required dedicated staff time and high-end equipment and hence are only conducted during specialized neurological examinations. To close this diagnostic and clinical monitoring gap, this work proposes a novel approach for tracking neurocognitive decline in the elderly by transitioning eye movement measurements from high-end, specialized medical equipment to low-cost ubiquitous consumer electronics, such as smartphones or tablets. Specifically, our approach displays eye movement tasks on iPads and uses the integrated selfie-camera to record videos of subjects completing these tasks on a daily basis. From the recordings, we extract eye movement features, identify and track eye movement abnormalities, and correlate them with neurocognitive decline. Our approach promises to enable continual and personalized tracking of neurocognitive decline from home. This will dramatically increase the granularity of assessment, thereby assisting doctors to discern normal, age-related neurocognitive decline from that seen in neurodegenerative diseases and providing an avenue for the development of more effective treatment plans and helping advance research into new treatment strategies.

Stochastic Regulator with Estimation Filter Implementable Using Bio/Nano Chemistry and Useful for "Intelligent Design"

J. M. Protz, A. Jain, A. Y.-H. Lee
Sponsorship: Protz Lab Group and the former BioMolecular Nanodevices, LLC

Signal processing using polymers has been a focus of the authors for two decades and has recently become of greater interest at MIT. Their present effort explores chemical and biological implementation of a stochastic linear regulator. It builds on a conceptual reaction mixture considered by the performer two years ago: "PROM" -type "junk DNA" in a plasmid transcribes into mRNA strands that are attacked by exonucleases coded for in a "BIOS" region of said plasmid; the activity of the nucleases depends jointly on the species of nucleotide being removed and on peptides pulled from polypeptides present alongside the plasmid; this causes the mix of surviving mRNA to depend on the polypeptide composition; the surviving mRNA reverse-transcribes into DNA that overwrites partly a "RAM" region of coding DNA in the plasmid, evolving it from a "prior estimate" of the environmental state to an "updated estimate" of the environmental state; said DNA expresses phenotypically as "actuator" proteins that are assembled by ribosomes from the free peptides and that "actuate" the surrounding environment; separately, a "sensor" reaction uses proteases and environmentally-sensitive peptide ligation reactions to recycle used "actuator" proteins back into free peptides that are then assembled into the aforementioned "sensor measurement" -storing polypeptides. One period of this cycle represents one update interval for an estimation filter. If implemented in a cell or organism, with the "sensor measurement" -storing polypeptides doubling as, e.g., a yolk, the lifetime of one cell or organism could constitute one update cycle of a stochastic regulator implemented by way of a cell line, organism family line, or society. Progress of the effort may allow the engineering of cell lines that evolve themselves and their environment deterministically and robustly according to "intelligent design" and may also explain the existence of aging, death, reproduction, and variable life expectancy.

Engineering High-throughput Electrokinetic Filtration for Nucleic Acid Enrichment

M.Cui, E.M. Wynne, J. Han
Sponsorship: U.S. Food and Drug Administration (FDA, 1R01FD007226-01)

Rapid and reliable ultralow-abundance molecular detection is of great interest in biomedical research and clinical trial. Quantitative polymerase chain reaction, a widely used nucleic acid quantification method, has multiple inherent issues, including tedious sample preparation, non-specific amplification, limited detection range, etc. Besides, there is no existing amplification method for protein, which restricts the development of protein-based diagnosis. Thus, there is a critical unmet need for a universal amplification or preconcentration of molecules.

Previously, our group developed a high-throughput electrokinetic filtration for biomolecule concentration. Although the flow rate is extremely high, the sample recovery rate is only 40% - 60%. Furthermore, the optimization of this concentrator is complicated because the device is not designed for microscopy. Herein, we propose a microscopic version of high throughput concentrator. This device allows imaging of concentration region, which provides a quantitative assessment of device performance. With the assistance of microscopy, we optimized the device, including minimizing downstream pore size on cation exchange membranes (CEMs) to ~150 μm in diameter to effectively generate ion depletion zones (IDZs), inserting ~35 μm porous polyethylene (PE) in front of IDZs to increase the electric intensity, adding ~25 μm porous filter paper near IDZs to compress instability of vortex. The operating flow rate can also be easily determined by downstream imaging. In summary, the microscopic device provides not only straightforward assessments of concentration but also operation at a high flow rate.

We used fluorescent-tagged DNA (ssDNA-647) in 0.1X phosphate buffer saline to test the performance of the device. With the assist of microscopic device, a flow rate up to 50 μL/min is achieved without significant leakage at 50 V. A 1 mL sample can be concentrated to a final volume of 50 μL, with a concentration factor of 20. We will further test the concentration performance of protein and bacteria.

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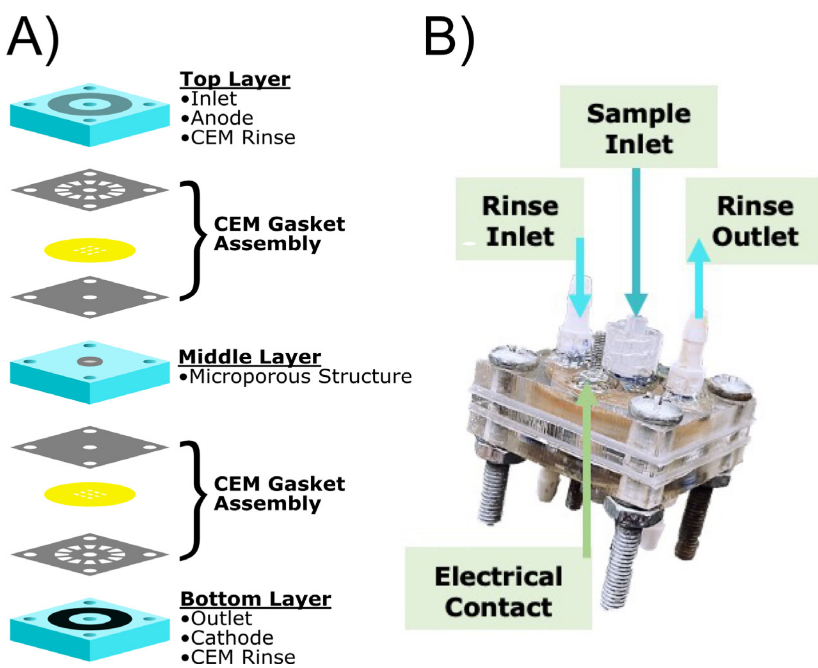
High Throughput Electrokinetic Concentrator with Polydopamine DNA Capture Substrate

E. M. Wynne, M. Cui, J. Han
Sponsorship: SMART CAMP

Technologies such as next-generation sequencing are able to detect small amounts of genetic material, making low abundance detection of pathogens a possibility. These technologies can only process volumes on the scale of tens of microliters at time, limiting the utility of these methods when trying to process large volumes such as liters of bioreactor supernatant. Electrokinetic concentration devices could elevate these sensing technologies by reducing large sample volumes to a scale more compatible with these technologies.

We demonstrate an EK concentration device operating at flowrates up to 50 microliters per minute, and characterize the performance when adjusting voltage, flowrate, and buffer composition. Our device uses an electric field to focus DNA into a region with a polydopamine (PDA) coated substrate that binds DNA. We demonstrate that applying a chelating agent to PDA releases the DNA such that it can quantified by methods other than fluorescence microscopy. This work expands the utility of EK concentration devices and presents a semi-continuous method for DNA enrichment in contrast to existing batch methods.



▲ Figure 1: A) A blown up schematic of the electrokinetic concentration device. B) A photograph of the device fully assembled.

Electrophoretic Quality Assessment of Adeno-associated Virus (AAV) by Microfluidic Ion Concentration Polarization

Y. Park, M. Cui, J. Han
Sponsorship: U.S. Food and Drug Administration (FDA, 1R01FD007226-01) and Singapore MIT Alliance for Research and Technology, CAMP IRG.

Adeno-associated virus (AAV) is widely used as a viral vector in gene therapies as well as genetic manipulation of various cells. The demand for high-quality AAVs is increasing alongside the growth of gene therapy. Still, there is a critical lack of reliable tools to assess the general quality of AAV capsids produced in biomanufacturing. However, AAV manufacturing in HEK293 always produces a very impure population, where only <30% of produced AAV particles typically have all the genes that make the particle functional in vivo [1]. Moreover, a large number of them are partially filled with genes that are not functional but have the potential to be immunogenic in vivo [2]. Therefore, detecting and potentially removing empty and partially filled AAV capsids is an important quality-control step in AAV biomanufacturing. This study tried to address this critical challenge by introducing a microfluidic device with the ion concentration polarization (ICP) effect. The ICP effect-based microfluidic device is fabricated based on previous research utilizing Nafion resin solution to make cation exchange membranes [3]. The device was tested using a reference AAV capsid to differentiate fully packed AAVs from empty AAV samples. The result was analyzed and quantified based on fluorescence intensity values of labeled AAV. The technique used in this study was able to distinguish a 5% content difference in each empty AAV composition ratio, suggesting a potential to be used as a tool for quantitative analysis in various studies like purification of particles with a similar size but different electric charge.

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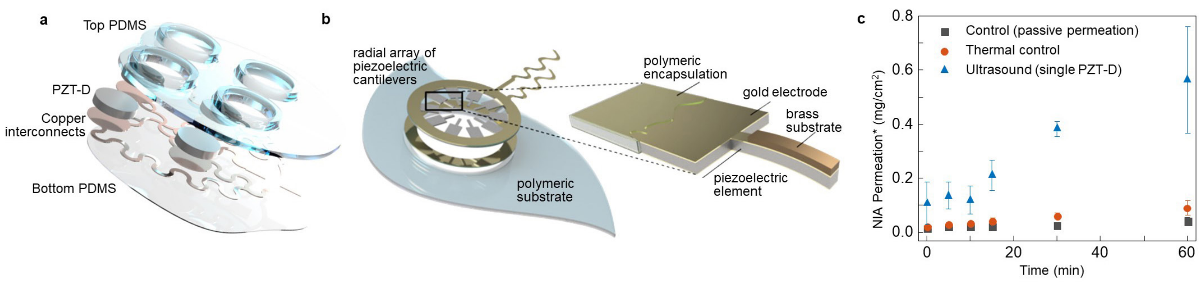
A Conformable Ultrasound Patch for Cavitation Enhanced Transdermal Cosmeceutical Delivery

A. Shah, C. Yu, N. Md Osman Goni, C. Marcus, C. Dagdeviren, A. Kumar-Bhayadiya
Sponsorship: MIT Media Lab Consortium, K.Lisa Yang Bionics Fellowship (AS, 2021-22), MIT Presidential Fellowship (AS, 2023-24), NSF CAREER: (Grant No. 2044688), 3M Non-Tenured Faculty Award, NSF (Grant No. s1905252).

Growing interest in skin health necessitates an effective method for enhancing the transdermal absorption of therapeutic cosmeceuticals such as niacinamide (122 $gmol^{-1}$). The challenge arises due to the limited permeation of such small-molecule drugs (<500 $gmol^{-1}$) through the stratum corneum barrier. We report a conformable ultrasound patch (cUSP) that employs intermediate-frequency sonophoresis to improve the transdermal transport of niacinamide. The cUSP, featuring bulk piezoelectric transducers within a soft elastomer, creates localized cavitation pockets (0.8 cm^2, 1 mm deep). Multiphysics simulations, acoustic spectrum analysis, and high-speed videography characterize transducer deflection, acoustic pressure fields, and cavitation bubble dynamics. In vitro testing on porcine skin demonstrates a 26.2-fold increase in niacinamide transport with a 10-minute ultrasound application. To further enhance portability, we propose miniaturizing the transducer footprint using piezoelectric unimorph cantilever structures to create a seamless conformable interface for patients suffering from skin conditions and premature skin aging.



▲ Figure 1: Simplified schematic, (not to scale) of the (a) bulk and (b) unimorph embodiments of the cUSP interface. (c) In vitro skin permeation results obtained with the bulk interface demonstrating a 19.2-fold enhancement in the total of niacinamide delivered in 60 minutes after 10 minutes of ultrasound application.

Ultrasound-based Detection and Sizing of Emboli: Toward Safer ECMO

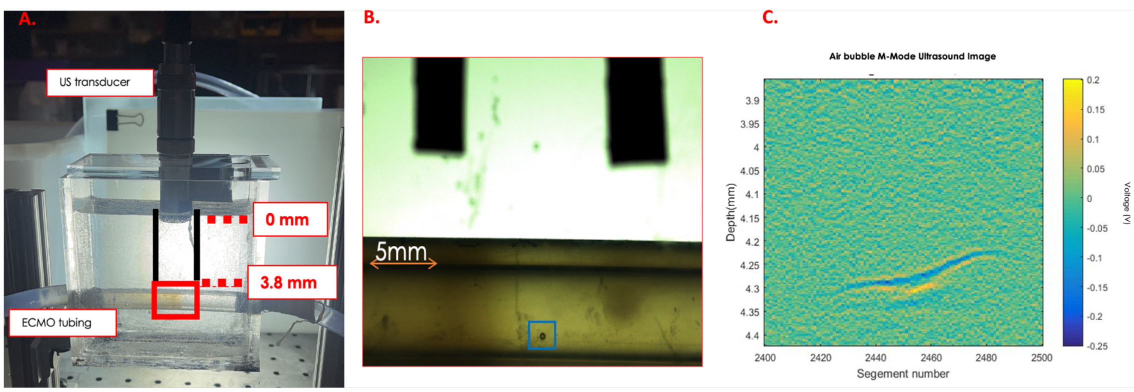
I. Romero, S. M. Imaduddin, T. Heldt, L. Bourouiba
Sponsorship: Boston Children's Hospital Anaesthesia Foundation

Extracorporeal membrane oxygenation (ECMO) is an extreme life-support mechanism designed to aid individuals whose lungs or heart is not functioning properly in oxygenating their blood. This process continuously pumps blood through an external device that adds oxygen and removes carbon dioxide.

However, ECMO comes with certain risks, including the potential formation of emboli, which can be either solid, such as blood clots, or gaseous, like air bubbles. Such emboli can lead to tissue damage through ischemia and may result in stroke or pulmonary obstruction, posing a substantial challenge in critical care. The detection and prevention of such emboli remain major technological challenges.

We aim to tackle this problem by leveraging ultrasonography. For that, we are collaborating closely with colleagues at Boston Children's Hospital and established a laboratory-based simulation system to replicate the clinical ECMO environment. We developed a data acquisition system for time-synchronized recording of ultrasound imaging and high-speed videography. This dual imaging approach allows for ground-truth recording of the emboli injected into this system. Finally, we have developed algorithms to analyze the recordings. By using signal processing techniques, we can detect, count, and size the emboli, thus paving the way for safer ECMO.

Future work will focus on improving the laboratory setting by using real blood clots and refining the algorithm to differentiate between solid and gaseous emboli. Additionally, expanding the application of these technologies to other forms of extracorporeal support systems will also be a priority, potentially broadening the impact of our work across different domains of critical care.



▲ Figure 1: A. Laboratory-based ultrasound data collection: Ultrasound transducer positioned perpendicular to the ECMO tube, with liquid flowing from left to right. B. High-speed videography for ground truth: Camera aligned with the ultrasound's focus area, capturing a 460-micrometer air bubble. C. Ultrasound imaging of the same air bubble: Air bubble represented in a color-scaled plot of segment number versus depth versus voltage.

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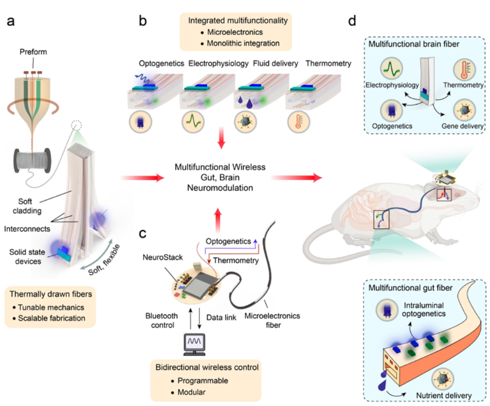
Multifunctional Microelectronic Fibers Enable Wireless Modulation of Gut-brain Axis

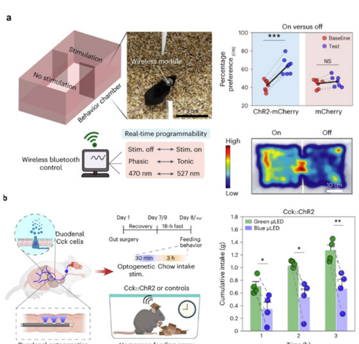
A. Sahasrabudhe, P. Anikeeva

The body's peripheral organs are in a constant bidirectional cross talk with the brain, generating a cognitive map of the body's physiological state, which is vital for survival. This is exemplified by the gut-brain communication, wherein hormonally and neurally mediated signals emerging from the abdominal viscera transduce metabolic information to the brain to maintain energy homeostasis. Although these internally arising gut-to-brain sensory cues are consciously imperceptible, they have been shown to influence neurocognitive processes such as motivation and affect. However, probing and understanding critical brain-body circuits in behaving animal models presents a neurotechnological challenge due to contrasting design criteria imposed on implantable devices by drastic anatomical differences between the skull-encased brain tissue and mobile, delicate peripheral organs.

Inspired by nerve fibers, we design a soft, flexible polymer fiber-based organ-brain neurotechnology. To match the inherent signaling complexity of the nervous system, we envisaged probes that integrate multiple functionalities yet retain a miniature device footprint to facilitate chronic bio-integration. To create a multifunctional and multi-organ neurotechnology, we combine the scalability and rapid customization of fiber drawing with the functional sophistication of solid-state microdevices (Figure 1a). We produce hundreds of meters of flexible polymer filamentary probes integrating microscale light-emitting devices, thermal sensors, microelectrodes, and microfluidic channels (Figure 1b). The ability to process thermoplastic elastomers with the same route enables deterministic tunability of device mechanics and allows probes of target deep-brain structures and/or regions of the murine intestine (Figure 1d, e). We design a lightweight and modular wireless control circuit, NeuroStack, that offers bidirectional wireless control and real-time programmability of in-fiber microdevices and an intuitive user interface (Figure 1c). The brain fibers offer gene delivery for cell-type specific optogenetic neuromodulation, single-neuron recordings, thermometry, and tetherless control of the mesolimbic reward pathway (Figure 2a). The soft gut fibers grant access to anatomically challenging, delicate intestinal lumen, allowing intraluminal optofluidic control of sensory epithelial cells that guide feeding behaviors (Figure 2b). We discover that optogenetic stimulation of vagal afferents from the intestinal lumen drives reward behavior in untethered mice. These illustrative applications foreshadow widespread use of wireless multifunctional microelectronic fibers to study the roles of specific cells in bidirectional communication between peripheral organs and the brain. This will empower the field of interoception, paving the way for mechanistically guided improved autonomic neuromodulation therapies.



▲Figure 1: Schematic illustration of microelectronics-integrated multifunctional fibers that enable wireless modulation of brain and gut neural circuits.



▲Figure 2: (a) Wireless brain devices allow modulation of neural circuits in deep brain reward structures as tested in real-time place preference assay in transgenic mice; (b) Wireless gut devices allow modulation of eneteroendocrine cells that signal satiety through hormone release in small intestine of mice as tested in acute feeding assay. devices allow modulation of eneteroendocrine cells that signal satiety through hormone release in small intestine of mice as tested in acute feeding assay.

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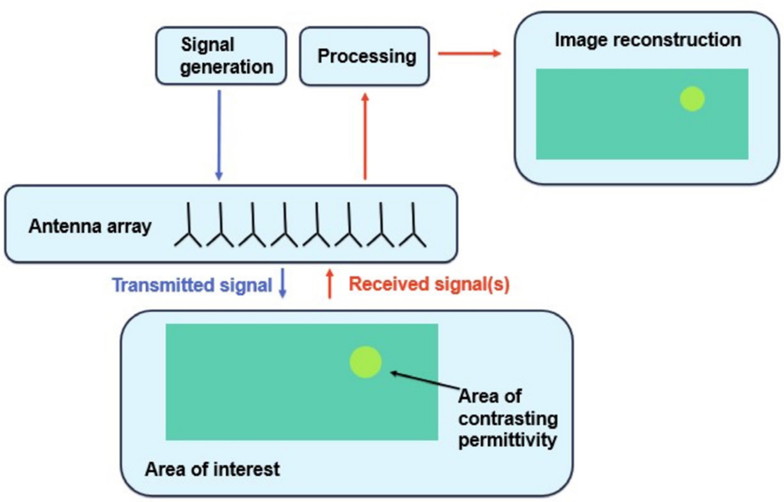
Miniaturization and Integration of Medical Microwave Imaging Systems

M. St. Cyr, A. Zarrasvand, N. Reiskarimian
Sponsorship: Draper Scholars

Microwave imaging (MWI) is an imaging modality of importance to numerous medical applications. Changes within the body are directly correlated to changing dielectric properties that correspond to different responses to an applied electric field. Thus, by sending a microwave signal into the body and detecting the transmitted and reflected signals from multiple locations surrounding the area of interest, an image can be reconstructed that demonstrates physiological changes. MWI is identified as a potential new harmless and noninvasive imaging modality for medical spaces such as tumor detection.

MWI requires sensitive and reliable electronics. Signal generators, transmitters, and receivers are some of the components needed to realize an MWI system. Early research on microwave imaging has used highly dependable off-the-shelf electronics; however, these electronics are often very bulky and unspecified to the application of MWI. By developing integrated circuits for MWI, we can make systems cheaper, smaller, and easier to operate. Such characteristics are necessary for continuous monitoring of conditions inside the body and overall higher accessibility to healthcare.

This work will design integrated circuits specifically for MWI. The goal is for these circuits to occupy a much smaller footprint than current electronic solutions, without compromising image quality. This work begins with understanding the challenges and tradeoffs that exist within off-the-shelf electronic systems through system level design exploration. After understanding the metrics in the electronic system that correlate with image quality, we will design circuit topologies to fit the exact specifications required.



▲ Figure 1: Overview of an MWI system.

Progress on an Implantable Microphone for Cochlear Implants

E. F. Wawrzynek, J. Z. Zhang, E. S. Olson, I. Kymissis, H. H. Nakajima, J. H. Lang
Sponsorship: NIDCD/NIH R01DC016874, NSF GRFP Grant No. 1745302, NSF GRFP Grant No. 2141064

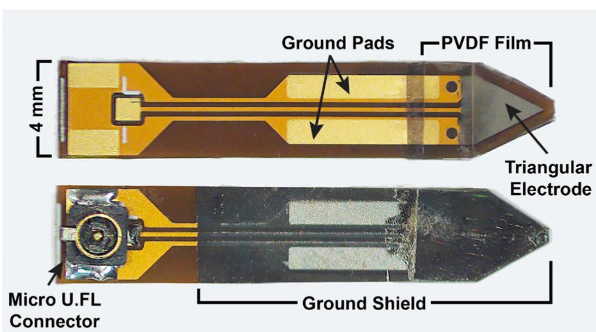
Cochlear implants are devices that can restore hearing loss to people with sensorineural hearing loss. Despite their name, cochlear implants rely on an external electret microphone which poses many lifestyle restrictions on the users. We present the fabrication and testing of an implantable microphone as an important step towards a totally implanted cochlear implant.

The piezoelectric microphone is made from titanium and thin film polyvinylidene fluoride (PVDF), is shaped like a triangular cantilever, and has a differential output. Figure 1 shows an image of the microphone sensor during and after fabrication. The microphone sensor is inserted through the facial recess and contacts the manubrium's umbo. We target the umbo because its uni-directional motion produces a well-represented sound signal. As the umbo moves, it displaces our piezoelectric sensor, resulting in a charge accumulation that we amplify with a custom differential charge amplifier.

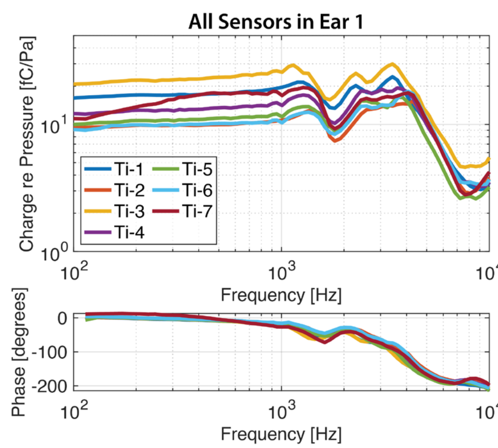
We use photolithography and thin film deposition to fabricate our sensors in a nano-microfabrication facility at the Massachusetts Institute of Technology. We have tested seven sensors at Mass Eye and Ear via bench testing and human cadaveric experimentation.

The eight sensors behave comparably during bench testing and in five distinct human cadaveric ears. Our microphones show a flat frequency response, high sensitivity, good linearity, and an equivalent input noise comparable to commercial hearing aid microphones. Figure 2 shows the frequency response of all seven sensors in a single ear, while Figure 3 shows the frequency response of a single sensor across five ears.

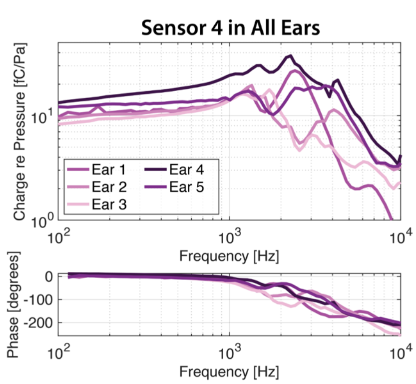
Our prototype demonstrates the feasibility of a PVDF-based microphone and is an important step towards developing a totally implantable cochlear implant.



▲Figure 1: A picture of two UmboMic sensors. The top sensor is partially fabricated; the triangular electrodes have been patterned, the flex PCB trimmed, and the PVDF layer adhered. It is missing the ground shield and U.FL connector which can be seen in the finished bottom sensor.



▲Figure 2: The frequency response of eight different microphones in a single ear. The y-axis shows the charge output of the microphone normalized by the pressure in the ear canal. Despite fabrication and implantation differences, the sensors have a very similar frequency response.



◀Figure 3: The frequency response of a single sensor in five different ears. Despite anatomical differences between ears, the sensor has a similar frequency response across experiments.

Piezoelectric Single Crystal-Based Ultrasound Patch for Breast Imaging

W. Du, L. Zhang, E. Suh, D. Lin, C. Dagdeviren
Sponsorship: NSF CAREER: Conformable Piezoelectrics for Soft Tissue Imaging (grant no. 2044688), NSF Graduate Research Fellowship Program under grant no. 2141064

Ultrasound is pivotal for breast cancer diagnosis, but challenges limit its integration with wearables, especially for large curvilinear organs. We've introduced a breakthrough: the cUSBr-Patch, a conformable ultrasound breast patch. This wearable offers standardized, reproducible image acquisition across the entire breast, reducing operator reliance and transducer compression. The honeycomb-shaped patch, guided by an easy-to-use tracker, enables large-area, deep scanning, and multiangle breast imaging. Using a piezoelectric crystal [Yb/Bi-PIN-PMN-PT], our in vitro and clinical trials achieved a contrast resolution of ~3 dB and axial/lateral resolutions of 0.25/1.0 mm at 30 mm depth. This allows the observation of small cysts (~0.3 cm) in the breast. Our technology provides a noninvasive method for real-time tracking of dynamic soft tissue changes, marking a significant advancement in ultrasound for breast tissue scanning within a compact wearable form.

MEMS, Field-Emitter, Thermal, Fluidic Devices & Robotics

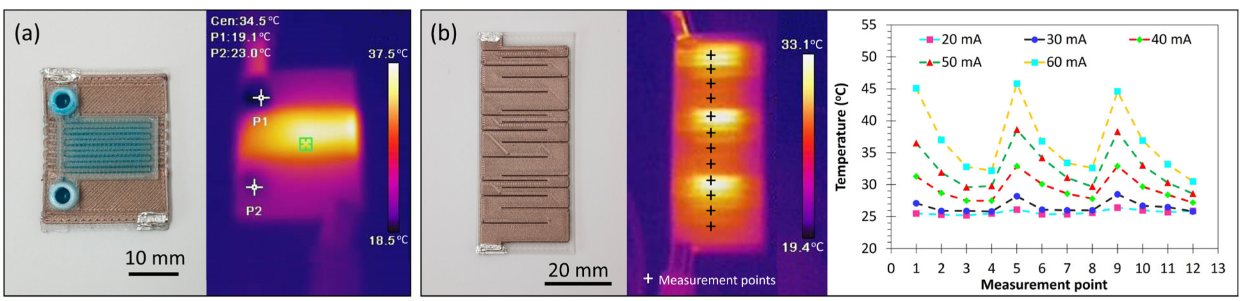
Fully 3D-printed, Monolithic, Self-heating Microfluidic Devices

J. Cañada, L. F. Velásquez-García
Sponsorship: Empiriko Corporation, “la Caixa” Foundation

Microfluidic devices allow manipulation and processing of small quantities of fluids by using sub-millimeter scale channels. Microfluidics are used extensively in industry and academia, with applications ranging from drug development to space propulsion. These applications often involve temperature-sensitive processes, e.g., manipulation of living cells, triggering of specific chemical reactions, which make temperature regulation critical. Temperature regulation techniques in microfluidics typically involve the use of bulky equipment external to the microfluidic device, and reports of microfluidics with integrated cooling-heating systems rely on costly fabrication processes and assembly steps.

This work proposes the use of multi-material extrusion three-dimensional (3D) printing to create monolithic, self-heating microfluidic devices in a single, inexpensive manufacturing operation. Material extrusion, also known as fused filament fabrication (FFF), creates parts by heating up feedstock and pushing it through a nozzle, constructing parts layer by layer. Material extrusion, a most accessible additive manufacturing technology, allows monolithic multi-material fabrication.

The proof-of-concept, self-heating microfluidic devices developed here consist of a 3D-printed resistor that acts as a heat source and a 3D-printed microfluidic channel that directs a fluid from an inlet to an outlet. This simple device demonstrates the ability of multi-material extrusion to produce microfluidic structures with monolithically integrated heating capability. The devices are fabricated using two polylactic acid-based materials: one is dielectric, used to produce the microfluidic channels and structural features; the other is electrically conductive, used to fabricate the resistors that serve as a heat source. The ability of material extrusion to create custom, intricate patterns enables fabrication of complex, application-specific designs of both the microfluidic structure and heating system. Future work includes studying the use of 3D printable materials as temperature sensors to enable closed loop temperature regulation.



▲ Figure 1: (a) Optical and thermal images of a 3D-printed, self-heating microfluidic device, and (b) Optical and thermal images, measured temperature profiles of custom 3D-printed heater.

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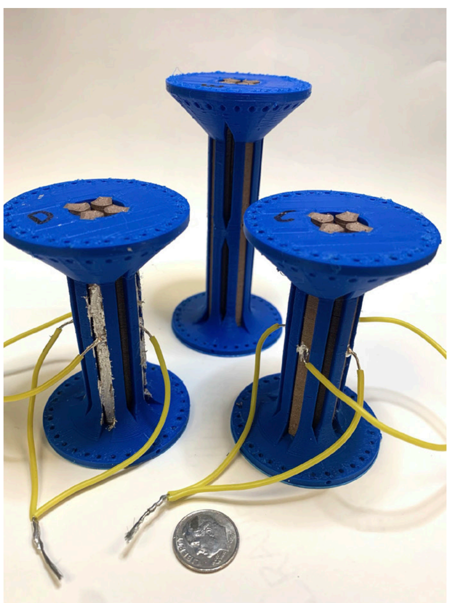
Miniaturized Quadrupole Mass Filters via Extrusion for Ionospheric Studies

A. Diaz, L. F. Velásquez-García
Sponsorship: MIT Portugal

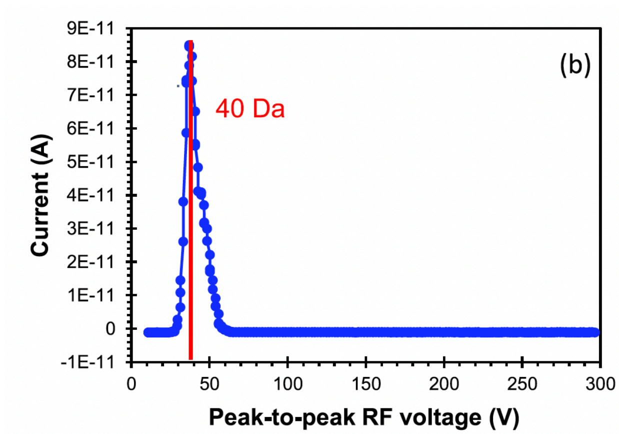
Mass spectrometry is the gold standard for quantitative chemical analysis. Mass spectrometers employ mass filters that sort out in vacuum the ionized constituents of a sample by mass-to-charge ratio. However, mainstream mass spectrometers are large, heavy, and power-hungry, restricting their ability to be deployed into CubeSats. Mass spectrometer miniaturization has been achieved at the expense of great loss in performance.

Quadrupoles are a popular choice for a mass filter due to their mass range, resolution, sensitivity, and sturdiness. Quadrupole mass filters use a combination of alternating and direct current voltages to contain species of a given specific charge, transmitting them from one end to the other of the quadrupole. Additive manufacturing makes it possible to create monolithically and precisely complex objects. Also, additive manufacturing is compatible with in-space manufacturing. Reports of 3D-printed quadrupole mass filters exist, but these are not monolithically made.

In this study, we developed novel, monolithically 3-D-printed quadrupole mass filters with hyperbolic rods (Figure 1). The devices are made via extrusion using polylactic acid (PLA) for the dielectric parts and PLA doped with copper nanoparticles for the conductive structures. The work included the development of compact, low-power, precision electronics to drive devices that are compatible with the size, weight, and power constraints of CubeSats. The devices satisfactorily detect argon—the heaviest gas found in the ionosphere (Figure 2).



▲Figure 1: Monolithically 3D-printed quadrupole mass filters next to U.S. dime for size comparison.



▲Figure 2: Mass spectra of argon using a 3D-printed quadrupole mass filter.

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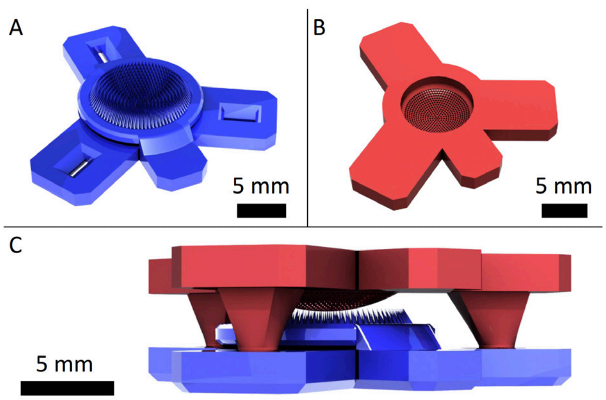
Curved Electron Sources for Next-Generation Electron Projection Lithography via Vat Photopolymerization and CNT Drop Casting

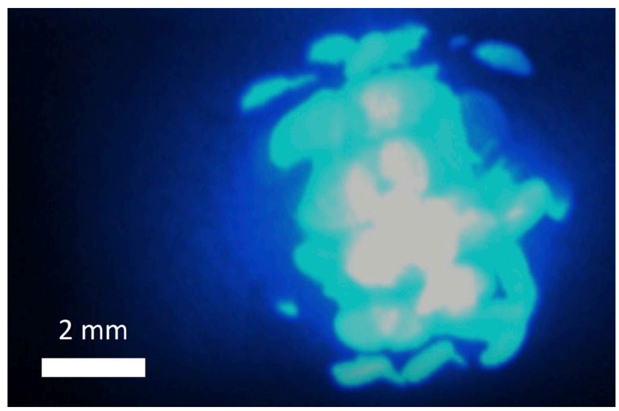
A. Kachkine, L. F. Velásquez-García
Sponsorship: MIT Portugal

Electron projection lithography (EPL) has the potential to surpass the resolution of mainstream extreme ultraviolet (EUV) lithography for chip manufacturing. Currently, the primary utility of EPL in industry is mask writing for EUV, where EPL beats classic electron beam lithography in terms of throughput. However, development of EPL for chip manufacturing has stalled due to throughput and process uniformity concerns.

We propose a new paradigm for EPL: a confocal electron source (Figure 1). In our de-sign, a monolithic array of micro/nanostructured cones is aligned with an extractor grid; emitted electrons converge onto a collector after a mask, resulting in pattern reduction. The absence of downstream lenses decreases substrate distance, enabling operation at lower electron energies and potentially increasing resolution. Emission of prototypes made via vat photo-polymerization and carbon nanotube drop casting attain a peak emission current of 300 μA/cm² (Figure 5). Time-series data shows emission stability. Phosphor screen imaging without a mask shows emission across the entirety of the device (Figure 2). Current research efforts seek to integrate masks into a prototype exposure column, while improving the emission uniformity and optical precision of the electron source.



▲Figure 1: Renderings of proposed EPL electron source. A) Emitter substrate showing cone decorated, revolved arc surface. B) Extractor with array of apertures. C) Assembled device showing confocal alignment via kinematic couplings.



▲Figure 2: Phosphor screen image of electron emission.

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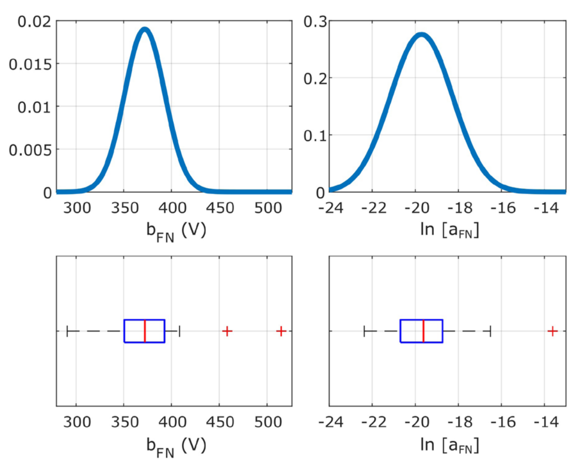
Silicon Field Emitter Arrays for Vacuum Integrated Circuits

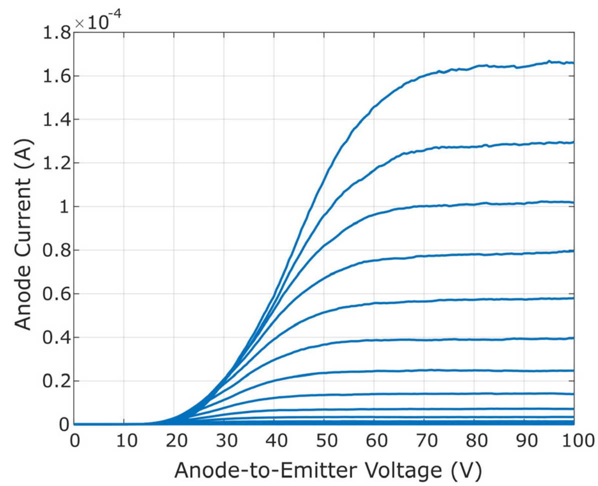
N. Karaulac, A. I. Akinwande
Sponsorship: U.S. Air Force Office of Scientific Research

Nanoscale vacuum-channel transistors are expected to show better performance in a wide variety of high-frequency, high-power, and/or harsh environment applications due to their ballistic transport and higher breakdown field. Silicon field emitter arrays (Si FEAs) are a proven and mature technology that can be implemented as vacuum transistors, and they could also be used in vacuum integrated circuits (ICs). Many of the challenges regarding uniformity, reliability, and lifetime have been addressed in this technology. Most recently, we addressed the scalability of the emission current by designing a layout-independent fabrication process for Si FEAs. However, several questions regarding the feasibility of vacuum ICs remain.

For digital and analog circuits, the transistor parameters must be closely matched, and the impact of variations in a_{FN} and b_{FN} on future vacuum ICs is unknown. In this work, we characterize and model the statistical variation resulting from our fabrication process. In Figure 1, we measure the transfer characteristics of 40 Si FEAs and extract a distribution of a_{FN} and b_{FN} values. We also measure the output characteristics of our devices in Figure 2 and fit the data using a compact model based on a sigmoid (s-shaped) function. Using this model, we perform a Monte Carlo simulation in LTspice of fundamental circuit building blocks, such as an inverter and current mirror, to analyze the impact of the variation of a_{FN} and b_{FN} on future vacuum IC performance.



▲ Figure 1: Box plots showing measured distribution of b_{FN} and ln[a_{FN}] from 40 Si FEAs ranging in size from single emitter to 1000x1000. Gaussian curves are fitted to the box plots.



▲ Figure 2: Measured output characteristics of 100x100 Si FEA for different values of gate-to-emitter-voltage, V_{GE}. More precisely, V_{GE} = 20, 22, ..., 48, 50 V.

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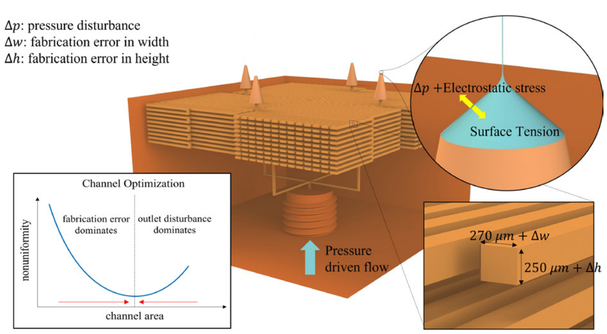
3D-printed Microfluidic Flow Distributor for Multiplexed Electrospray Droplet Thrusters

H. Kim, L. F. Velásquez-García
Sponsorship: MIT Portugal

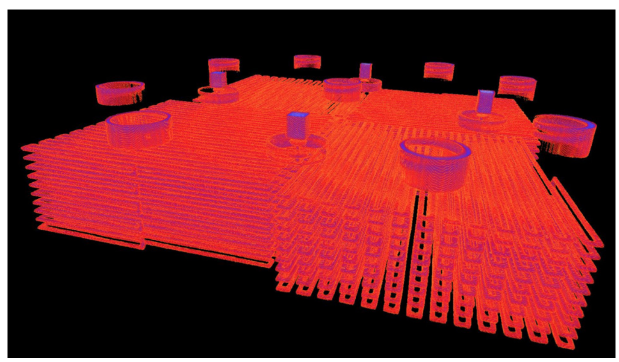
Electrospray propulsion, accomplished by electrohydrodynamically ejecting charged corpuscles of propellant, offers several advantages for propelling small spacecraft like CubeSats. Its capacity to achieve high specific impulse using electrical power rather than being constrained by the chemical energy of the fuel is particularly noteworthy. Also, electrospray thrusters' bipolar emission obviates the need of a neutralizer. However, a single electrospray emitter provides limited thrust because electrospray emission is possible only within a limited range of fuel flow rates. In the higher flow rate regime within this range, the emitted particles are mostly droplets, resulting in higher thrust than the lower flow rate regime emitting ions. Nonetheless, thrust remains constrained, scaling with the flow rate to the power of ¾. This thrust constraint necessitates multiple emitters, with uniform operation being crucial to avoid efficiency degradation or emitter flooding. Miniaturization of the electrospray hardware introduces benefits, e.g., lower start-up voltage.

Traditionally, miniaturized electrospray thrusters have been fabricated in a semiconductor cleanroom. However, this method is very expensive, time-consuming, and incompatible with in-space manufacturing. While 3D-printed, uniformly operating ion-emitting electrospray thruster arrays have been successfully demonstrated, implementing a 3D-printed droplet-emitting thruster has proven challenging. The main challenge lies in fabricating a uniform flow distributor that can tolerate fabrication errors and withstand dynamic outlet conditions caused by non-uniform electric field and interfacial effects, aspects often overlooked by typical bifurcation distributors or other geometries.

To address this challenge, we optimized the design of a uniform flow distributor to cope with fabrication errors and outlet pressure perturbations (Figure 1). Using this framework, we 3D-printed a four-emitter prototype with modified liquid resin capable of printing narrow channels (Figure 2). The prototype exhibited uniform flow distribution while delivering a flow rate up to ~0.1 mm³/s to each emitter of the ionic liquid 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF_4)—a propellant commonly used in electrospray propulsion.



▲Figure 1: 3D schematic of the flow distributor with sources of non-uniformity explained.



▲Figure 2: Reconstructed 3D image of the flow distributor from an X-ray microscope.

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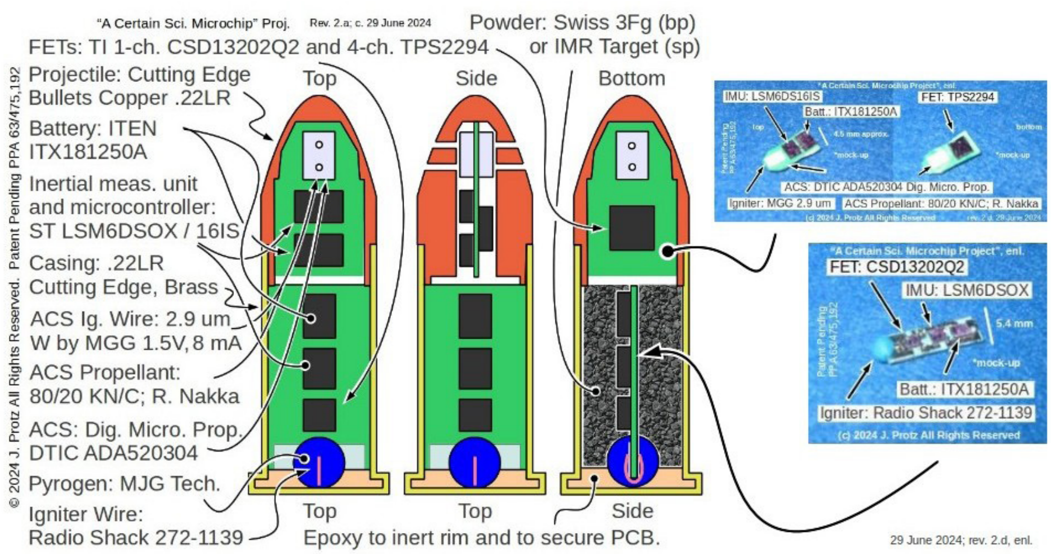
Qualitative Modeling of an Electron Transiting a Vacuum with Drag and Lo-Fi TOE

J. Protz, J. Gerson, P. Kelly, A. Jain, A. Lee
Sponsorship: Protz Lab Group; the former microEngine, LLC and Asteria Propulsion LLC

Study at MIT of the link between the Kalman filter and quantum physics goes back to 1980 and the publication of S. Mitter's LIDS-P-1006; comparable work was published in Japan in 2014 by Ishikawa and Kikuchi and in China in 2022 by Ma, Kong, Wang, and Luand. In 2023, at IVNC at MIT, the present investigator proposed that devices maneuvering in air according to Boyd's energy-maneuverability theory for aircraft (with steady throttle to overcome steady drag, unsteady throttle for maneuver, and throttle lag) could provide an analogy for electrons in the vacuum and that the modeling of groups of such particles might allow the construction of a sort of "lo-fi" fully classical "theory of everything" that reproduces qualitatively many artifacts found in relativity and quantum mechanics and observed experimentally. In the works mentioned above, the irreducible quantum uncertainty of quantum mechanics shows as the driving noise of a system tracked by a Kalman filter; here, said driving noise is caused by throttle lag making it not possible to cancel with made thrust the bombardment of the electrons by the smaller particles that compose the vacuum. The project is at an early stage, and the modeling continues; presently, it is focused on making a "video game physics engine". Separately, silicon MEMS propulsion was studied at MIT for two decades; recently, the present investigator has been considering a MEMS chip that would combine a computer, sensors, and a micro rocket motor into a device that could replace a .22 LR bullet's primer cap in NCAA and Olympic competitive sport shooting. A conceptual design has been completed and is illustrated in the figure below. If successful, the project could lead to a class of sport shooting that features teams having both athletes and device engineers in the same way that does auto racing.



▲ Figure 1: conceptual design of a .22 LR digital bullet cartridge for NCAA and Olympic -type sport shooting; chip set used for optical image stabilization (OIS) in digital cameras placed here in casing and used to correct for hand jitter; similar chip set inside projectile enables limited in-flight steering.

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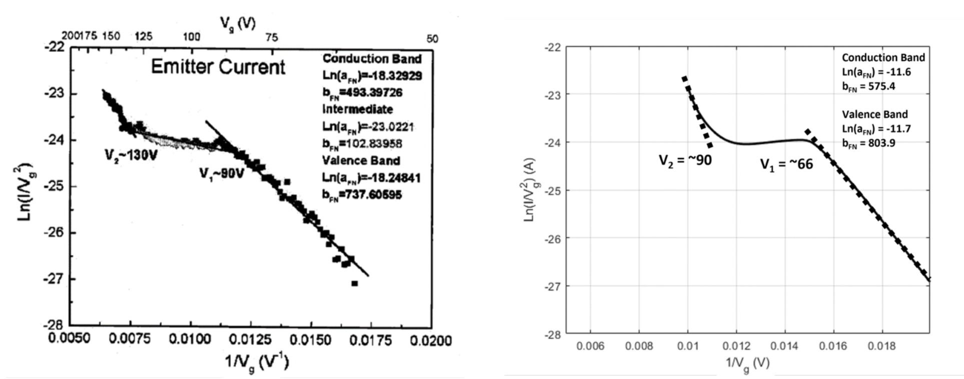
Second Exponential Region in Silicon Nanowire Field Emitter Arrays: Impact Ionization, Direct Band-to-Band Tunneling, or Valence Band Emission?

A. Sahagun, A. I. Akinwande
Sponsorship: U.S. Air Force Office of Scientific Research

At high gate-to-emitter voltages for silicon nanowire field emitter arrays (FEAs), the Fowler-Nordheim (FN) plot shows an unexpected increase in emission current despite the emission current being supply-limited. The second exponential region beyond the supply-limited region in the FN plot might be explained by impact ionization in the semiconductor due to the strong electric field. Other proposals hypothesize that the second exponential region is due to direct band-to-band tunneling resupplying the conduction band for electron emission. However, in the aforementioned cases, the FN slope ($-b_{FN}$) in the second exponential region should remain the same as in the first exponential region; this is not observed experimentally, as shown in Figure 1 a). The difference in the slope of the second exponential region may be due to an increase in the barrier height seen by electrons tunneling from the valence band into vacuum. However, no simulations of this valence band emission have been performed to sup-port this result.

In this work, we aim to simulate the second exponential region in the field emission current observed experimentally and explore if the second exponential region results from im-pact ionization, direct band-to-band tunneling, or valence band emission. We use a physics- based approach (SILVACO) to simulate the tunneling probability at both the conduction band and valence band energy levels and the FN slopes. Using SILVACO, we recreated the device structure reported in the literature and simulated it. Preliminary results, shown in Figure 1 b), demonstrate that a sharp increase in emission current exists at high gate-to-emitter voltage after the supply-limited region. Extracting and comparing the slopes of both exponential re-gions, we find that the ratio is 1.4 in the simulation and 1.49 in the experimental data, which are both close to the suggested slope ratio of 1.45, indicating a two-band field emission model. Additional work explored impact ionization, direct band-to-band tunneling, and valence band emission.



a) b)

▲Figure 1: a) Experimental results from a Si NW field emitter with conduction and valence band emis-sion. b) Simulation results from a Si NW field emitter with impact ionization occurring.

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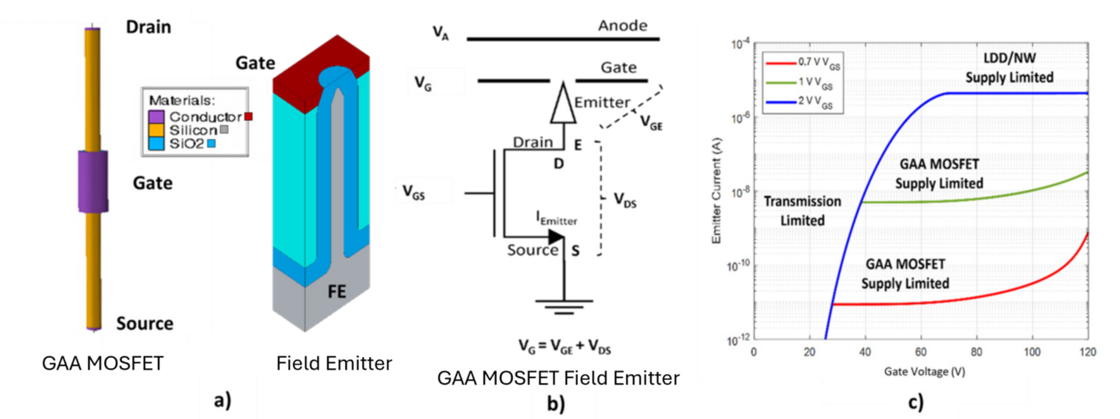
Programmable Current Control of Silicon Field Emitter Arrays Using Gate-all-around MOSFETs

A. Sahagun, A. I. Akinwande
Sponsorship: U.S. Air Force Office of Scientific Research

Silicon field emitter array (FEA) technology has great potential for applications such as electron microscopy, vacuum electronics, and X-ray sources. However, some challenges such as emitter tip burnout and spatial and temporal non-uniformity of emission current impede the adoption of FEAs in these applications. The state-of-the-art approach to addressing these challenges involves integrating a nanowire (NW) current limiter in series with the emitter tips to regulate current flow. The NW current limiter is preferred for its compact integration, which enables high emitter density in FEAs. However, the limiter restricts FEA versatility by constraining the emission current to a fixed maximum value. In contrast, metal–oxide–semiconductor field-effect transistors (MOSFETs) can provide programmable control over emission current. However, integrating planar MOSFETs into FEAs demands significant space, leading to a notable reduction in emitter tip density, FEA compactness, and performance.

In this work, we investigate the integration of vertical gate-all-around (GAA) MOSFETs with individual emitter tips shown in Figure 1 a) and b) to enable programmable emission current control while preserving the compactness, high emitter density, and versatility of FEAs. We use a physics-based approach (SILVACO) to model and simulate the integrated GAA MOSFET-FE device. The simulation results provide insight into the device's I-V characteristics, identifying performance-limiting challenges such as impact ionization occurring in the field emitter and GAA MOSFET. To address the breakdown inherent in GAA MOSFETs, a lightly doped drain, acting essentially as an NW, is included. Preliminary results in Figure 1 c) show the ability of the gate-to-source voltage (V_{GS}) of the GAA MOSFET to transition the field emission process from a transmission-limited region to a supply-limited region.



▲Figure 1: a) Two individual components: a vertical GAA MOSFET structure obtained in SILVACO and a cutline of a single field emitter from an array with an integrated gate (anode not imaged). b) A series combination of the vertical GAA MOSFET in series with the field emitter. c) Simulation results for GAA MOSFET-FEA I-V characteristics, where VGS is varied from 0.7 V to 2 V.

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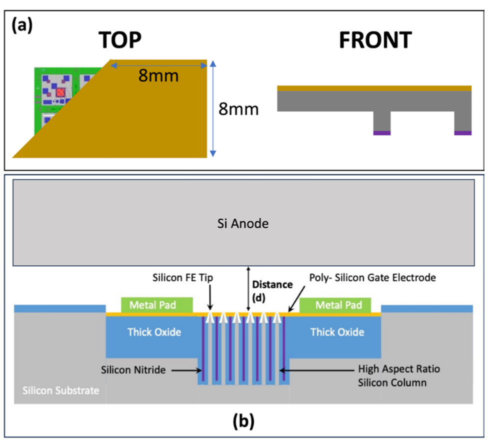
Field Emitter Arrays Device Characteristics–A Closer Look at Space-charge

Y. Shin, W. Chern, N. Karaulac, A. I. Akinwande
Sponsorship: AFOSR

Field emitter array- (FEA) based cold cathodes have shown promise as electron sources in devices capable of high power and high frequency operation for a variety of applications such as microwave power amplifiers, pressure sensors, x-ray sources, and high-power excimer lasers. Limited work has explored the device characteristics using well defined cathode-to-anode separation. Consequently, FEAs lack a physics-based compact model.

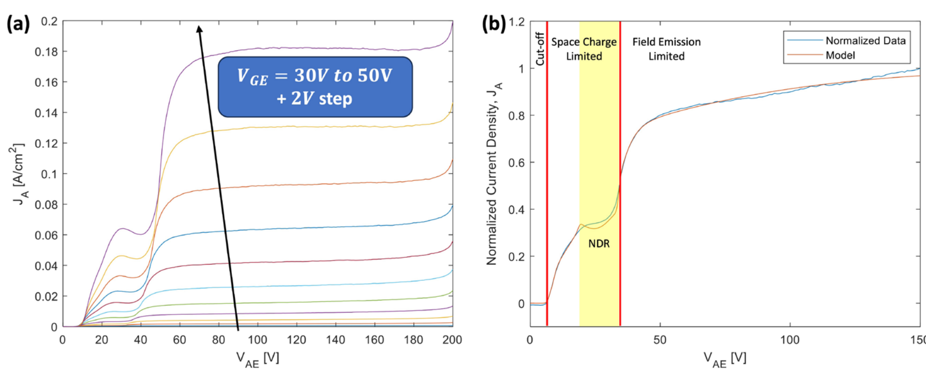
In this work, a flat stand-off anode was placed on the FEAs, which guarantees the anode distance and the parallel condition. The anode geometry and experimental configuration are shown in Figure 1a. The I-V characteristics in the space charge limit show an unexplained, yet reproducible negative differential resistance (NDR) region (Figure 1b). These results imply that the development of a model for FEAs will need to account for additional phenomena affecting electron transport in the space between the anode and the gate electrode.

Upon further analysis of the experimental configuration, the electrostatic simulations reveal that a decelerating potential exists in the space between the parallel gate and anode electrodes. The deceleration of the emitted electrons occurs when the anode-to-emitter voltage, V_{AE}, is lower than the gate-to-emitter voltage, V_{GE}. The resulting output characteristics with a fitted model appear in Figure 2. The I-V characteristics were modeled using a semi-empirical approach due to the still ambiguous physical effects caused by the decelerating potential. The model demonstrates good accuracy under typical operating conditions of the experimental configuration. The resulting FEA model opens new avenues of applications including oscillators and amplifiers.



◀ Figure 1: (a) Final anode geometry with proposed integration in relation to device chip and (b) schematic of experimental configuration including details of device structure.

▼ Figure 2: (a) Output characteristic sweep from V_{GE} = 30V to 50V and (b) normalized output characteristic of 1000 x 1000 FEA overlayed by model fitted at V_{GE} = 34V. Main operating regimes are labeled; NDR region highlighted.



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Nanoscience & Nanotechnology

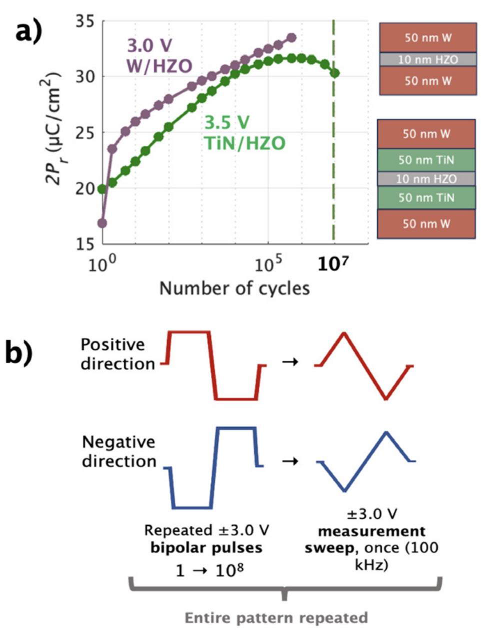
Characterization of Ferroelectric Endurance in $Hf_{0.5}Zr_{0.5}O_2$ Deposited by Plasma-enhanced ALD

T. E. Espedal, Y. Shao, E. R. Borujeny, J. A. del Alamo
Sponsorship: MIT Undergraduate Research Opportunity Program, Intel Corporation, Semiconductor Research Corporation

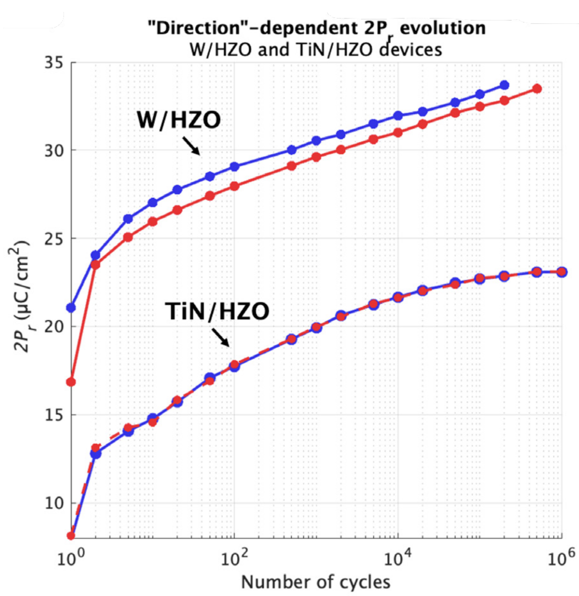
Among different non-volatile memory (NVM) technologies, ferroelectric (FE) memory based on complementary metal-oxide semiconductor- (CMOS) compatible $Hf_{0.5}Zr_{0.5}O_2$ (HZO) has emerged as one of the most promising, as it could potentially provide low-voltage operation, fast switching, long data retention, and high device endurance. Plasma-enhanced atomic layer deposition (PEALD) has shown film quality that might lead to improved memory behavior in HZO. However, a detailed study of endurance in PEALD HZO, and more importantly the role of various process conditions, is needed. In this work, we study the endurance characteristics of PEALD HZO in a capacitor configuration, processed with different metal electrode W or TiN, Figure 1.

We study the endurance characteristics by applying 3.0 V bipolar pulses followed by a triangular diagnostic waveform, from which we extract remnant polarization (Figure 2) and coercive field. Using a pulse amplitude of 3.0V, TiN devices yield a lower remnant polarization than W devices, since the 3.0 V voltage applied is a suitable value for W devices but relatively low for TiN. We also observe symmetric wakeup in TiN devices, compared to asymmetric wakeup in W devices under the same conditions (Figure 2). This indicates different changes in the respective metal/HZO interfaces that appear with repeated cycling. Furthermore, we observe early breakdown in W devices without apparent fatigue (Figure 2), while we see clear wake-up and fatigue stages with much longer endurance cycles (>107 for 3.5 V; Figure 1) in TiN counterparts.

Our work shows that the choice of metal in a FE HZO structure has significant effects on device wake up and endurance. Analyzing these effects is important for identifying the optimal HZO device structure and process conditions for eventual NVM applications.



▲Figure 1: a) Endurance of W/HZO and TiN/HZO at 3.0V and 3.5V, respectively; the last point measured is just before device breakdown. Note the presence of fatigue in TiN/HZO devices. On the right, schematic of device structure. b) Measurement scheme for cycled endurance V-t.



▲Figure 2: Evolution of remnant polarization, 2Pr, dependent on direction of ±3.0 V bipolar pulse cycling and ±3.0 V triangular I-V measurement sweep.

Robust DNA-patterned Glass Surfaces with Micrometer Features by Photolithography and Click Chemistry.

E. Perry, J. Tiepelt, J. Jacobson
Sponsorship: Media Lab Consortia

The ability to precisely pattern DNA onto glass is paramount for various bio-analytical applications, including DNA microarrays, biosensors, microfluidics, next-generation sequencing, and lab-on-a-chip. Contemporary fabrication techniques often employ printing technologies such as inkjet, piezoelectric, and contact printing for precise droplet placement followed by chemical immobilization. Alternatively, photolithographic exposure can activate or deactivate custom-designed regions of the surface to be patterned with biomolecules. DNA immobilization unto the glass is commonly achieved by Streptavidin-Biotin interactions or the use of silanized surfaces. Both methods are well established yet carry certain disadvantages and complexities, specifically when combined with advanced microfabrication processes to generate micron and submicron patterns.

In this work, we propose a novel method to fabricate robust DNA-patterned glass surfaces with micron-scale features. The innovation in this approach is the combination of copper-free click chemistry with a biocompatible photolithographic process. Copper-free click chemistry is based on the reaction of diaryl cyclooctene (DBCO) with an azide-labeled reaction partner. In our process, azide-coated glass is first masked by direct-write photolithography followed by plasma ashing, to generate reactive azide regions underneath the photomask. Room-temperature suspension of DNA molecules modified with DBCO leads to covalent attachment of DNA strictly to the active regions. Our preliminary results show this process generates patterned surfaces with a very high signal-to-noise ratio compared to standard techniques, as well as stability and resistance to denaturing conditions. Our method could appeal to researchers interested in custom in-house fabrication of pristine DNA-coated surfaces.

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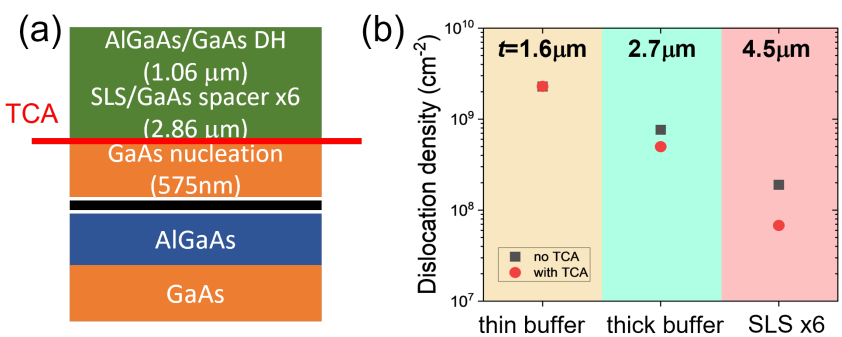
- D. Melo Máximo and L. F. Velásquez-García, "Additively Manufactured Electrohydrodynamic Ionic Liquid Pure-ion Sources for Nanosatellite Propulsion," *Additive Manufacturing*, vol. 36, p. 101719, 2020, doi: 10.1016/j.addma.2020.101719.

Engineering Defects in Remote Epitaxial III-V Materials Grown on Thin Amorphous Carbon

N. M. Han, K. Lu, H. Kim, S. Cho, J. Kim
Sponsorship: Defense Advanced Research Projects Agency, United States Air Force Research Laboratory, Department of Energy, Rohm Semiconductor, LG, Umicore, Universiti Tenaga Nasional

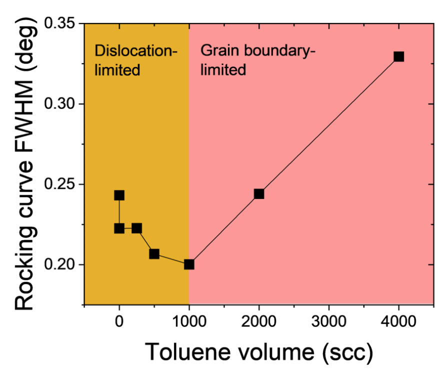
Remote epitaxy has emerged as a facile technique for producing freestanding, wafer-scale membranes of single-crystalline semiconductors. However, it still encounters challenges but also presents other benefits when compared to direct epitaxy. In the case of growing epitaxial layers on the same or lattice-matched substrates, remote epitaxy results in lower material quality and higher defect density due to the attenuated atomic registry from the substrate. To address this issue, we propose the incorporation of thermal cycle annealing (TCA) and strained layer superlattice (SLS) into the growth process, as illustrated in Figure 1a, which effectively reduces the threading dislocation density by a few orders of magnitude, as shown in Figure 1b.

Conversely, when the substrate and epitaxial layer have a high lattice mismatch, remote epitaxy offers an advantage through the van der Waals interface, which provides an additional pathway to relax the strain developed in heteroepitaxial layers. This spontaneous relaxation mechanism significantly reduces the occurrence of misfit dislocations that are commonly observed in direct heteroepitaxy. By directly growing thin amorphous carbon (TAC) on GaAs, by-passing the need for a 2D layer transfer process, we can create an ultra-thin van der Waals interface that enhances the atomic registry of the epitaxial layer to the substrate while facilitating strain relaxation. In this study, we investigate the impact of TAC growth time on the material quality of remote heteroepitaxial InGaAs layers grown on GaAs substrates, as shown in Figure 2. The inherent strain relaxation capabilities offered by remote epitaxy enable the heteroepitaxy of high-quality membranes on lattice-mismatched substrates, paving the way for the fabrication of diverse electronic and optoelectronic devices.



◀ Figure 1: (a) Schematic of thermal cycle annealing (TCA) and strained-layer superlattice (SLS) and (b) their influence on the dislocation density of remote-epitaxial GaAs.

▶ Figure 2: Effect of in-situ grown graphene thickness, represented by volume of toluene precursor flown, on quality of InGaAs grown on GaAs substrate (low rocking curve full width at half maximum indicates better quality).



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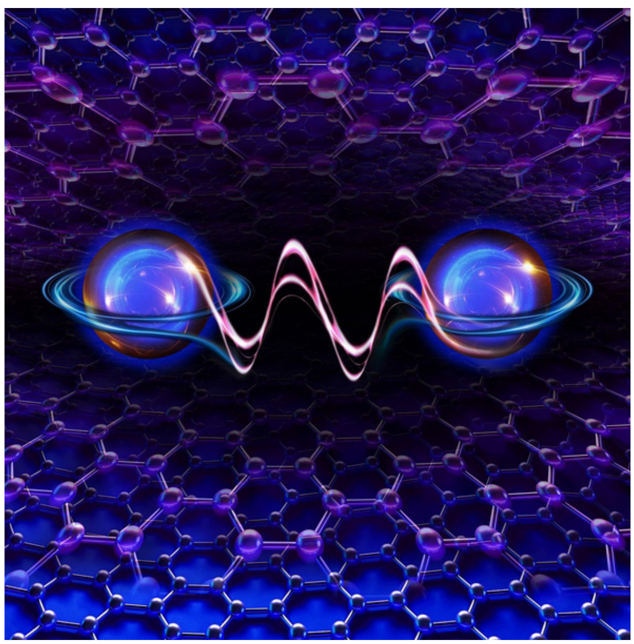
Correlated Insulator and Chern Insulators in Rhombohedral Pentalayer Graphene

T. Han, Z. Lu, G. Scuri, J. Sung, J. Wang, T. Han, K. Watanabe, T. Taniguchi, L. Fu, H. Park, L. Ju
Sponsorship: Sloan Fellowship, NSF

Rhombohedral-stacked multilayer graphene hosts a pair of flat bands touching at zero energy, which should give rise to correlated electron phenomena that can be tuned further by an electric field. Moreover, when electron correlation breaks the isospin symmetry, the valley-dependent Berry phase at zero energy may give rise to topologically non-trivial states. Here we measure electron transport through hexagonal boron nitride-encapsulated pentalayer graphene down to 100 mK. We observed a correlated insulating state with resistance at the megaohm level or greater at charge density $n = 0$ and displacement field $D = 0$. Tight-binding calculations predict a metallic ground state under these conditions. By increasing D, we observed a Chern insulator state with $C = -5$ and two other states with $C = -3$ at a magnetic field of around 1 T. At high D and n, we observed isospin-polarized quarter- and half-metals. Hence, rhombohedral pentalayer graphene exhibits two different types of Fermi-surface instability, one driven by a pair of flat bands touching at zero energy, and one induced by the Stoner mechanism in a single flat band. Our results establish rhombohedral multilayer graphene as a suitable system for exploring intertwined electron correlation and topology phenomena in natural graphitic materials without the need for moiré superlattice engineering.



▲Figure 1. Resistance of rhombohedral pentalayer graphene as function of charge density and gate-displacement field. Blue dot corresponds to correlated insulator state; purple and yellow dots correspond to quarter and half-metals, respectively. Red star corresponds to valley-polarized metal state.

FURTHER READING

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The Oxidation Sequence of Ultrathin Hafnium Metal on Graphene

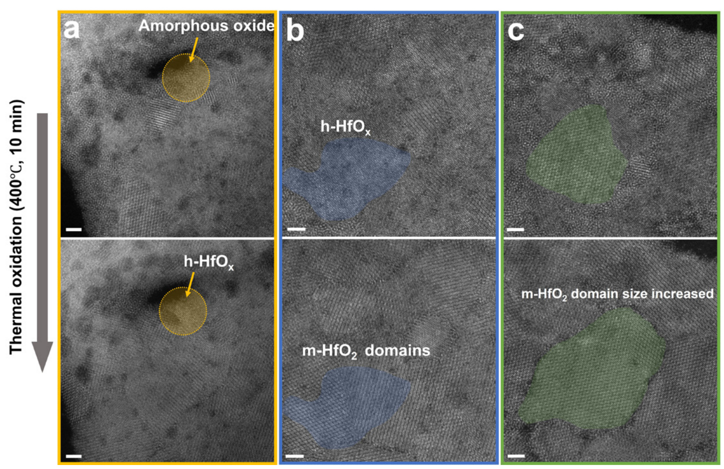
Z. Liu, R. Jaramillo, F. M. Ross
Sponsorship: SRC (Contract No. 2021-NM-3027)

Hafnium oxides with their rich crystal phases are an important family of electronic materials based on their high dielectric constants, ferroelectric properties, and application in resistive switching random access memory. Understanding the oxidation of ultrathin hafnium (Hf) film at the atomic level will offer opportunities for the phase engineering of hafnium oxides towards different applications.

Here, starting with the epitaxial deposition of Hf on graphene carried out in ultra-high vacuum, we demonstrate that exposure to air at room temperature for only a few minutes results in the formation of several oxide phases (Figure 1, top row). These are an amorphous oxide, a hexagonal structure (h-HfO_x), and a monoclinic HfO_2 (m-HfO_2). We find the h-HfO_x phase to be intermediate in composition and structure between hcp Hf and m-HfO_2. The m-HfO_2 exhibits three equivalent orientations on the Hf crystal, which can be understood through its lower structural symmetry compared to the parent Hf hexagonal close packed (hcp) structure.

Further thermal oxidation of samples displaying these three structures results in the crystallization of some amorphous regions into h-HfO_x and conversion of the amorphous and hexagonal structures to m-HfO_2 (Figure 1, bottom row). Based on the crystallographic orientation relations observed, for the conversion of Hf to m-HfO_2 it is necessary for the stacking sequence of Hf layers in the out-of-plane direction to change from the AB stacking of hcp Hf to the ABC stacking of m-HfO_2. We expect this change in stacking sequence to lead to the appearance of a hexagonal pattern when imaged. We therefore propose that h-HfO_x, which displays a hexagonal pattern, contains sequences of AB and ABC stacked Hf layers in the out-of-plane direction.

By examining the structural changes and hence the atomic oxidation mechanism of ultrathin Hf using electron microscopy, we aim to clarify the opportunities for achieving phase control of hafnium oxides. These results are also relevant to solving the key issue of scalable formation of a conformal dielectric on two-dimensional (2D) materials such as graphene or transition metal dichalcogenides, by separating the growth process into first obtaining epitaxy between the metal and 2D material, followed by epitaxy of the oxide layer.



▲Figure 1: Oxide transitions during thermal oxidation, observed before and after thermal oxidation by scanning transmission electron microscopy (STEM). (a) Crystallization of amorphous oxides into h-HfO_x. (b) Conversion from h-HfO_x to m-HfO_2. (c) STEM images showing the transformation of larger m-HfO_2 grains.

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Orbital Multiferroicity in Rhombohedral Pentalayer Graphene

T. Han, Z. Lu, G. Scuri, J. Sung, J. Wang, T. Han, K. Watanabe, T. Taniguchi, L. Fu, H. Park, L. Ju
Sponsorship: Sloan Fellowship, NSF

Ferroic orders describe spontaneous polarization of spin, charge, and lattice degrees of freedom in materials. Materials exhibiting multiple ferroic orders, known as multiferroics, play important roles in multifunctional electrical and magnetic device applications. Two-dimensional materials with honeycomb lattices offer opportunities to engineer unconventional multiferroicity, in which the ferroic orders are driven purely by the orbital degrees of freedom and not by electron spin. These include ferro-valleytricity corresponding to the electron valley and ferro-orbital-magnetism supported by quantum geometric effects. These orbital multiferroics could offer strong valley–magnetic couplings and large responses to external fields, enabling device applications such as multiple-state memory elements and electric control of the valley and magnetic states.

We observed orbital multiferroicity in pentalayer rhombohedral graphene using low-temperature magneto-transport measurements. We observed anomalous Hall signals R_{xy} with an exceptionally large Hall angle ($\tan\Theta_H > 0.6$) and orbital magnetic hysteresis at hole doping. Four such states exist with different valley polarizations and orbital magnetizations, forming a valley–magnetic quartet. By sweeping the gate electric field E, we observed a butterfly-shaped hysteresis of R_{xy} connecting the quartet. This hysteresis indicates a ferro-valleytronic order that couples to the composite field $E \cdot B$ (where B is the magnetic field), but not to individual fields. Tuning E would switch each ferroic order independently and achieve non-volatile switching of them together. Our observations demonstrate a previously unknown type of multiferroics and point to electrically tunable ultralow-power valleytronic and magnetic devices.

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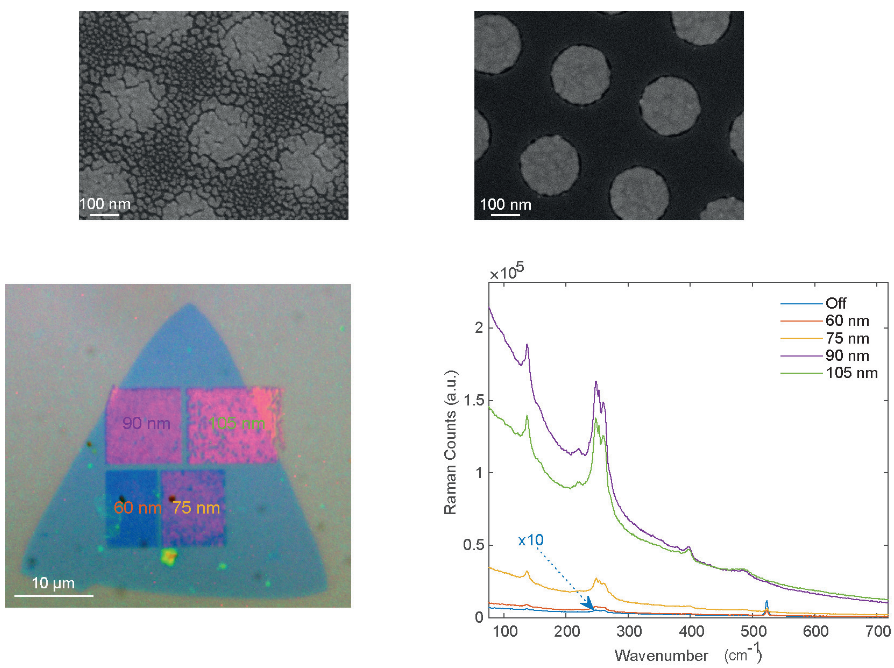
Tailoring Light Emission and Scattering from Atomically Thin Materials with Transferable Nanostructures

A. K. Demir, J. Li, T. Zhang, C. Occhialini, L. Nessi, J. Kong, R. Comin
Sponsorship: U.S. Department of Energy, Office of Science National Quantum Information Science Research Center's Co-design Center for Quantum Advantage (C2QA) under contract number DE-SC0012704, Raith VELION FIB-SEM in the MIT. nano Characterization Facilities (Award: DMR-2117609), MathWorks Science Fellowship (Award: 4000182189)

Optical spectroscopy is indispensable for unveiling the unique properties and symmetries of materials in the atomically thin limit. However, the vanishing thickness often leads to a cross section too low for conventional optical methods to work. In this work, we developed a technique, completely dry and simple to implement, to fabricate and transfer high-resolution optical enhancement nanostructures for Raman and PL spectroscopy. We demonstrate orders-of-magnitude increase in the intensities of single-layer WSe_2 phonon modes; enabling the detection of phonon modes of three-layer NiI_2 using non-resonant excitation; and selective Purcell enhancement of the quenched excitons in WSe_2/MoS_2 heterostructures. We also highlight that the method is particularly suitable for optical studies of air-sensitive materials, as the fabrication and transfer can be performed in situ.

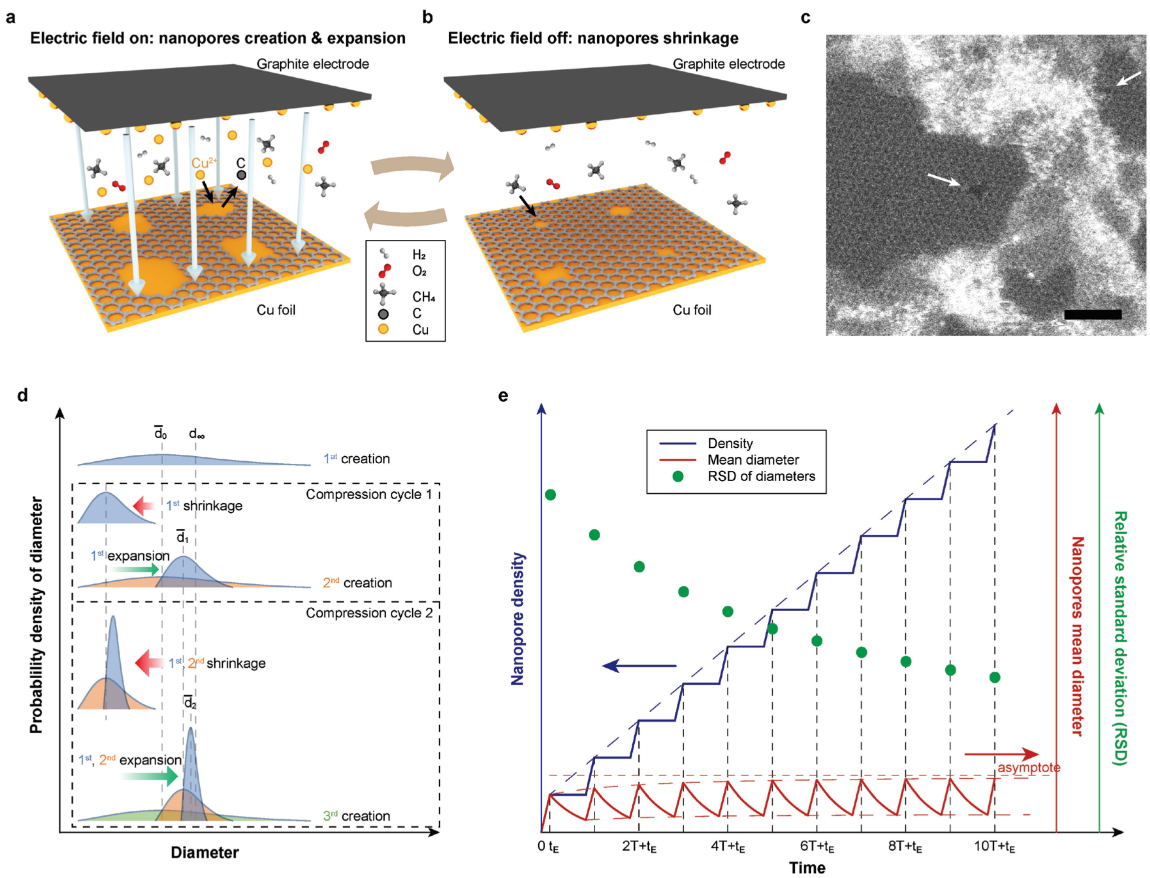


▲ Figure 1: Top Panel: Our method provides significant increase in the quality of the nanostructures fabricated without adhesion layers. Bottom Panel: Lack of the adhesion layer enables us to transfer the nanostructures on van der Waals materials, resulting in a large enhancement of the optical signal.

Cascaded Compression of Size Distribution of Nanopores in Monolayer Graphene

J. Wang, C. Cheng, X. Zheng, T. Zhang, J. Kong
Sponsorship: U.S. Army Research Office, U.S. Department of Energy

Monolayer graphene, featuring nanometre-scale pores and exceptional mechanical properties, is ideal for ion/molecular separations, energy storage, and electronics. Precise engineering of nanopore size and distribution is crucial for these applications. Top-down methods typically result in log-normal size distributions with long tails, especially at subnanometre scales, and a trade-off between nanopore size distribution and density limits their practical use. Here, we report a cascaded compression method for producing graphene nanopores with a narrowed, left-skewed size distribution and ultrashort tail deviation (Fig. 1). This process involves sequential steps where existing nanopores undergo both shrinkage and expansion, simultaneously creating new nanopores and enhancing overall density. The result is graphene nanopores with high density, left-skewed distribution, enabling ultrafast, size-tunable transport of ions and molecules. This technique offers independent control over nanopore density, diameter, deviation, and distribution skewness, potentially revolutionizing nanotechnology.

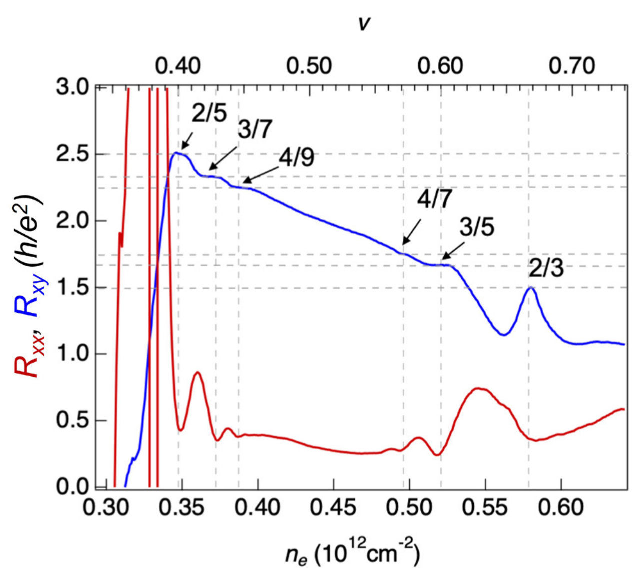


▲ Figure 1: Cascaded compression cycles. a, Creation & expansion of nanopores by Cu sputter. b, Shrinkage of nanopores by regrowth. c, STEM image of nanopores. Scale bar, 2 nm. The schematic evolution of d, the probability density of diameter, and e, nanopore density, mean diameter, and RSD vs. time.

Fractional Quantum Anomalous Hall Effect in Graphene

Z. Lu, T. Han, Y. Yao, A. P. Reddy, J. Yang, J. Seo, K. Watanabe, T. Taniguchi, L. Fu, L. Ju
Sponsorship: Sloan Fellowship, NSF

The fractional quantum anomalous Hall effect (FQAHE), the analogue of the fractional quantum Hall effect at zero magnetic field, is predicted to exist in topological flat bands under spontaneous time-reversal-symmetry breaking. The demonstration of the FQAHE could lead to non-Abelian anyons that form the basis of topological quantum computation. So far, the FQAHE has been observed only in twisted $MoTe_2$ at a moiré filling factor $v > 1/2$. Graphene-based moiré superlattices are believed to host the FQAHE with the potential advantage of superior material quality and higher electron mobility. Here we report the observation of integer and fractional QAH effects in a rhombohedral pentalayer graphene–hBN moiré superlattice. At zero magnetic field, we observed plateaus of quantized Hall resistance $R_{xy} = h/(ve^2)$ at v = 1, 2/3, 3/5, 4/7, 4/9, 3/7, and 2/5 of the moiré superlattice, respectively, accompanied by clear dips in the longitudinal resistance R_{xx}. R_{xy} equals $2h/e^2$ at v = 1/2 and varies linearly with v, similar to the composite Fermi liquid in the half-filled lowest Landau level at high magnetic fields. By tuning the gate-displacement field D and v, we observed phase transitions from composite Fermi liquid and FQAH states to other correlated electron states. Our system provides an ideal platform for exploring charge fractionalization and (non-Abelian) anyonic braiding at zero magnetic field, especially considering a lateral junction between FQAHE and superconducting regions in the same device.



▲ Figure 1: R_{xx} and R_{xy} in the rhombohedral pentalayer graphene/hBN moiré superlattice. Clear plateaus of R_{xy} at $5h/(2e^2)$, $7h/(3e^2)$, $9h/(4e^2)$, $7h/(4e^2)$, $5h/(3e^2)$ and $3h/(2e^2)$ emerge at filling factor v = 2/5, 3/7, 4/9, 4/7, 3/5 and 2/3, as indicated by the dashed lines and arrows. R_{xx} shows clear dips at the corresponding filling factors. These fractional states host fractionally charged quasiparticles with fractional statistics.

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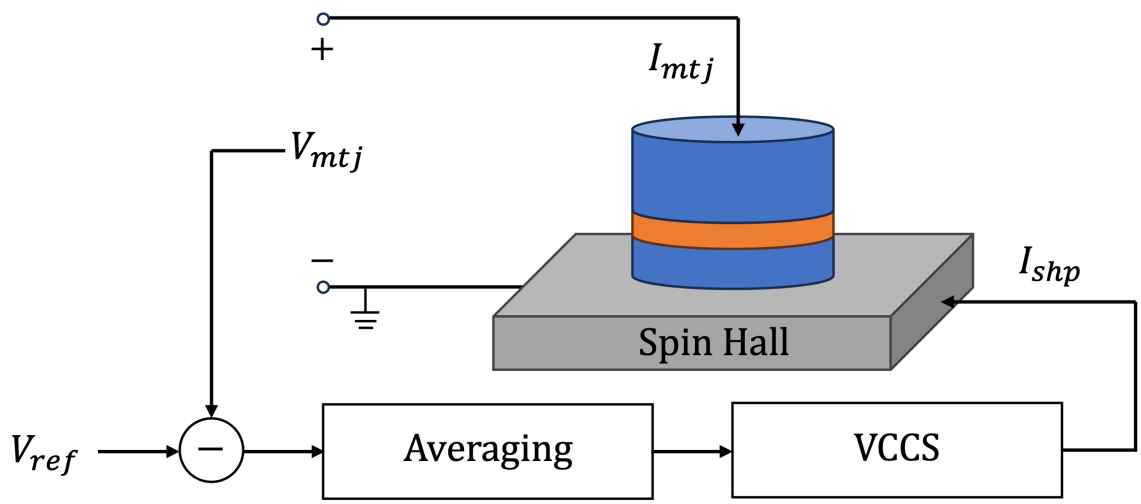
Towards Uniform Probabilistic Distribution in Superparamagnetic Tunnel Junctions

D. Koh, B. C. McGoldrick, L. Liu, M. A. Baldo
Sponsorship: Semiconductor Research Corporation Supreme #3137.009

Stochastic algorithms, which employ statistical methods with random numbers, are prevalent in fields such as cryptography and machine learning. Conventional computers, however, produce random bitstreams via pseudo-random number generators. These bitstreams, while appearing random, actually possess long-range orders, reducing their effectiveness for many stochastic algorithms. Superparamagnetic tunnel junctions have emerged as candidates for scalable and energy-efficient true random number generators. Yet, achieving a uniform probabilistic distribution, a critical requirement for most stochastic algorithms, is challenging with a single nanomagnet. In this work, we explore an approach to enforce a uniform distribution in the device's probabilistic output and assess its impact on the true randomness. This method not only promises faster and more energy-efficient random number generation but also opens possibilities for integrating massive stochastic nanomagnets into large-scale systems.



▲ Figure 1: Conceptual diagram of controlling probability distribution by utilizing current-induced spin-orbit-torques in three-terminal superparamagnetic tunnel junctions.

Tunable Mechanical Response of Self-Assembled Nanoparticle Superlattices

S. Dhulipala, D. Yee, Z. Zhou, R. Sun, J. E. Andrade, R. J. Macfarlane, C. M. Portela
Sponsorship: National Science Foundation (NSF) CAREER Award CMMI-2142460, U.S. Army Research Office under Grant W911NF-18-1-0197, NSF CAREER Award CHE-1653289, and the Department of the Navy, Office of Naval Research, under ONR award number N00014-22-1-2148

Self-assembled nanoparticle superlattices (NPSLs) are an emergent class of self-architected nanocomposite materials that possess promising properties arising from precise nanoparticle ordering. Their multiple coupled properties make them desirable as functional components in devices where mechanical robustness is critical. However, questions remain about NPSL mechanical properties and how shaping them affects their mechanical response. Here, we perform in-situ nanomechanical experiments that evidence up to an 11-fold increase in stiffness (~1.49 to 16.9 GPa) and a 5-fold increase in strength (~88 to 426 MPa) because of surface stiffening/strengthening from shaping these nanomaterials via focused-ion-beam (FIB) milling. To predict the mechanical properties of shaped NPSLs, we present discrete element method (DEM) simulations and an analytical core–shell model that captures the FIB-induced stiffening response. This work presents a route for tunable mechanical responses of self-architected NPSLs and provides two frameworks to predict their mechanical response and guide the design of future NPSL-containing devices.

Novel Tellurium Contacts for P-type WSe_2 Devices

H. W. Lee, J. Zhu, K. Reidy, F. Ross, J. Kong, T. Palacios
Sponsorship: Intel (ISRA)

Since the first discovery of graphene, extensive research on two-dimensional (2D) materials has opened promising possibilities for elevating 2D semiconductor applications from the academic to the industrial level for the next generation of electronics. Now, 2D semiconductors can be grown at a large scale, processed using CMOS-compatible fabrication techniques, and demonstrate high-performance transistors with low contact resistance. However, these remarkable improvements have mainly been achieved with n-type 2D semiconductors, primarily focusing on molybdenum disulfide (MoS_2). In the case of p-type 2D semiconductors, such as tungsten diselenide (WSe_2), there are still significant challenges in material growth and reducing contact resistance to make them comparable to n-type 2D transistors. These challenges hinder the demonstration of 2D complementary metal-oxide-semiconductor (CMOS) circuits at an industrial level. In particular, reducing the contact resistance between a p-type 2D channel and a metal contact is essential to achieving high-performance p-type transistors.

In this work, we explore the use of semimetal tellurium (Te) as contacts for p-type WSe_2 transistors. Semimetals such as bismuth (Bi) and antimony (Sb) are known to mitigate the Fermi level pinning effect at the interface between the metal and MoS_2, thereby drastically reducing the contact resistance of MoS_2 transistors [1]. We compare the performance of WSe_2 transistors with various contact materials, including Te, palladium (Pd), and platinum (Pt), and observe that Te contacts indeed reduce the Fermi level pinning effect at the interface of WSe_2 and Te. In addition, we enhance the performance of WSe_2 transistors by adjusting the deposition temperature of Te. This research on semimetal Te contacts will serve as an important baseline study for novel contacts for p-type 2D transistors, thereby enabling the next generation of commercialized 2D electronic devices.

Optimizing the Radiative Lifetimes of Perovskite Nanocrystals for Quantum Emission Applications

K. McFarlane-Connelly, N. Brown, M. G. Bawendi
Sponsorship: US Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under award no. DE-SC00216

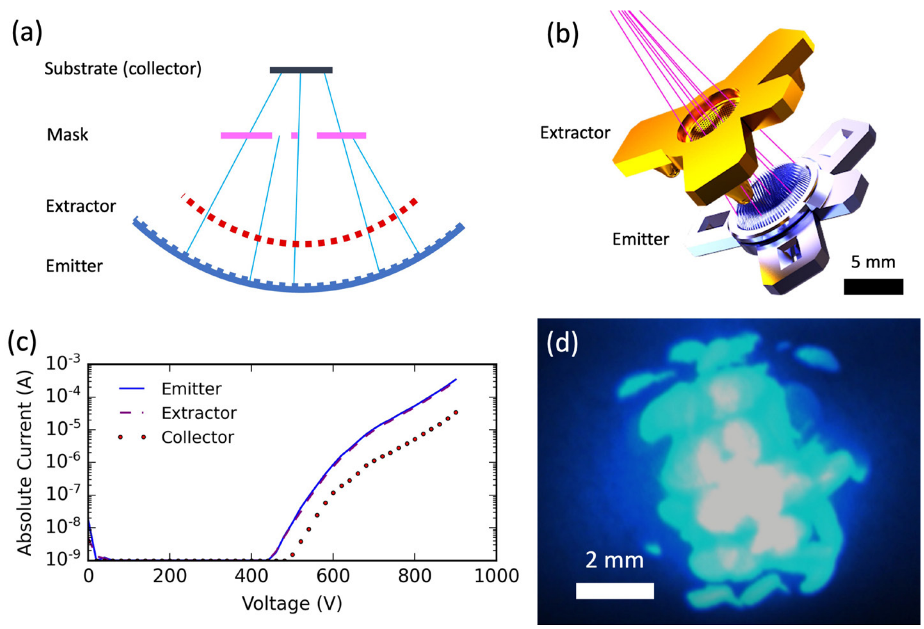
Realizing practical quantum computing schemes would fundamentally shift our technological capabilities. Imperative to this innovation is the scalable fabrication of quantum emitters (QEs). Ideal QEs approach the transform-limit ratio where the optical coherence lifetime (T_2) of the emission is twice the radiative lifetime (T_1). Large colloidal semiconductor nanocrystals (NCs) are promising QE candidates, however concrete methods of further minimizing their T_1 lifetimes are necessary. While theories have suggested T_1 values might scale inversely proportional to volume, this hypothesis remains unexplored. This research aims to elucidate the impact of size on the quantum emission properties of weakly confined perovskite nanocrystals. By tuning precursor chain lengths, a size series of highly luminescent $CsPbBr_3$ nanoparticles were prepared with extremely narrow size distributions. Five distinct sizes of nanocrystals were prepared in the weakly confined regime ranging from 16 to 23 nm, with standard distribution of sizes less than 7%. Post synthetic treatments were employed to boost photoluminescence quantum yields to higher than 80% at room temperature for all samples. The radiative lifetimes of these particles were observed under cryogenic temperatures revealing T_1 values that scaled inversely with particle size, providing experimental confirmation of theoretical predictions. These results demonstrate that increasing particle size is a promising route to approaching the ideal transform limit ratio with NCs. This fundamental work aims to enables future optimization of the quantum emission properties of weakly confined nanocrystals in hopes of realizing a path to scalable quantum emitter materials.

3D-Printed, Non-Planar Electron Sources for Projection Lithography

A. Kachkine, C. E. Owens, A. J. Hart, L. F. Velásquez-García
Sponsorship: NewSat Project, COMPETE 2020, ERDF, MIT Portugal Program, Mathworks

Photolithography resolution is diffraction-limited, while electron projection lithography (EPL), though higher resolution, is throughput-limited by electron divergence from planar sources. We report the first non-planar electron sources for EPL, a design paradigm with potential to overcome both limitations.

Fabricated by 3D printing, devices deliver confocal emission, achieving focusing and demagnification. Emission is produced by a concave dish base with an array of carbon nanotube-coated emitters aligned to the apertures of a concave extractor electrode; both are fabricated by vat photopolymerization 3D printing and modified by subsequent coatings. Our prototype device exhibits a startup voltage of 500 V, a peak emission current of 300 μA/cm^2, and a field enhancement factor of 7.8×10^4 cm^{-1}. Phosphor screen imaging of the devices in operation demonstrates that the emission is spatially uniform. Our approach enables compact design at industrial specifications of next-generation EPL systems.



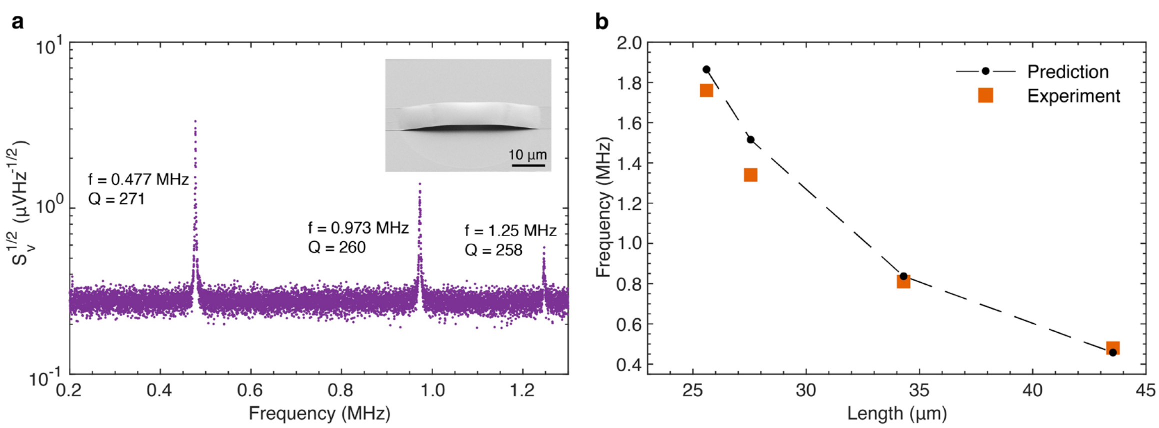
▲ Figure 1: (a) Proposed convex electron source schematic. (b) Device rendering, showing electron paths in pink. (c) Voltage sweep data from device in triode configuration. (d) Phosphor screen image of electron emission.

Designer Ultrathin Resonators using Delamination Lithography

S. O. Spector, P. F. Satterthwaite, F. Niroui
Sponsorship: NSF Graduate Research Fellowship

Thin-film, suspended mechanical resonators are a crucial component of nanoelectromechanical systems, from frequency conversion for radio signals to mass spectroscopy for biological sensing. Yet, the inherent instability of conventional, top-down fabrication techniques limits how thin these devices can be made, hampering their sensitivity and potential frequency range.

Here, we show that a nonplanar nanofabrication technique can be used to produce stable, ultrathin mechanical resonators (Figure 1a). By engineering surface forces using a molecular monolayer and simultaneously controlling the stress in a thin film, three-dimensional "delamination lithography" is achieved. We demonstrate that these devices, which we can design across a broad range of sizes using simple, wafer-scale techniques, conform to their theoretical and simulated behavior (Figure 1b), suggesting applications in designer resonators across frequency orders of magnitude.

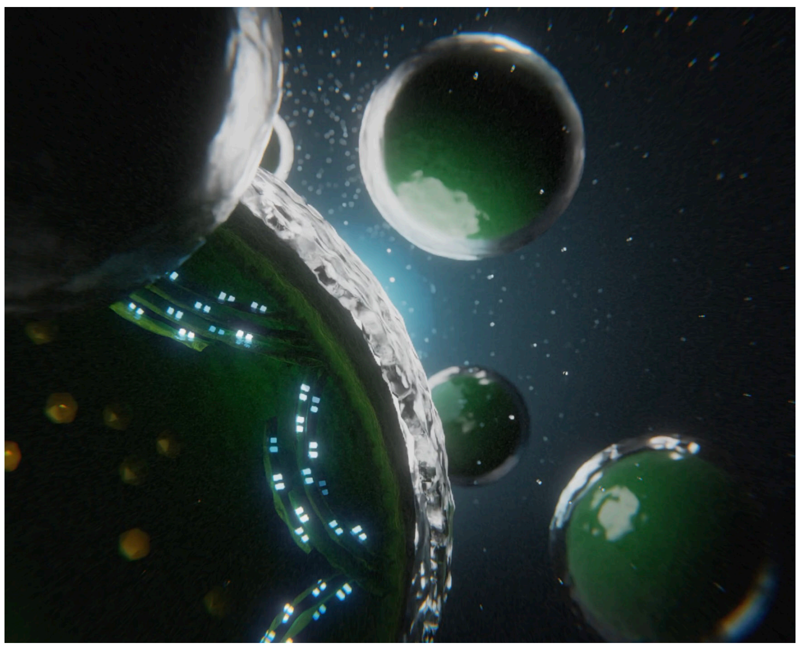


▲ Figure 1:(a) First three vibrational modes of a < 30 nm-thin suspended resonator shown in the inset SEM. (b) The fundamental frequency of the resonator as a function of its length, showing a close match between experimentally-measured and simulated results.

Rewiring Photosynthesis

T. Baikie
Sponsorship: The Lindemann Fellowship

Photosystems II and I (PSII, PSI) are the reaction centre-containing complexes driving the light reactions of photosynthesis. The impressive efficiencies of the photosystems have motivated extensive biological, artificial and biohybrid approaches to 're-wire' photosynthesis for higher biomass-conversion efficiencies and new reaction pathways. Electron extraction at earlier steps, perhaps immediately from photoexcited reaction centres, would enable greater thermodynamic gains; however, this was believed impossible with buried reaction centres. We demonstrate extraction of electrons directly from photoexcited PSI and PSII. Our results challenge previous models of photoexcited reaction centres and opening new avenues to study and re-wire photosynthesis for biotechnologies and semi-artificial photosynthesis. Here, we demonstrate, using in vivo ultrafast transient absorption (TA) spectroscopy, extraction of electrons directly from photoexcited PSI and PSII at early points (several picoseconds post-photo-excitation) with live cyanobacterial cells or isolated photosystems



▲ Figure 1: Artists impression of cell environment

Parameters Extraction for a Superconducting Thermal Switch (hTron) SPICE Model

V. Karam, O. Medeiros, M. Castellani, R. Foster, T. Dandachi, K. Berggren
Sponsorship: Breakthrough Starshot Initiative, DOE microelectronics

Superconducting nanowire circuits have shown great potential in photon sensing, demonstrating remarkable efficiency in extreme conditions while having large gains and high fanout. Yet, their integration into complex circuits is not as developed as other superconducting technologies. Their scaling is partly limited by a lack of effective simulation tools for superconducting nanowires, preventing designers from getting behavioral insights prior to fabrication.

As circuits increase in size and complexity, the modeling needs to shift from modeling detailed physical interactions to overall behavior of devices. For example, the multilayered heater-nanocryotron (hTron) device – a superconducting nanowire-based switch [1] – which has demonstrated applications in cryogenic memories, neuromorphic computing, and SNSPD array readout [2], was previously simulated using traditional finite-element modeling (FEM) methods, solving heat diffusion differential equations. However, while FEM techniques simulate individual superconductors accurately, they fall short in simulating larger circuits. Behavioral models are better adapted to that purpose, but require a large number of measurements to accurately reproduce the device's behavior.

In this work, we collect measurement data on the performance of 17 hTron devices and develop a method to extract physical fitting parameters from the measurement curves. Finally, we validate our model by performing the SPICE simulation of a 1:4 hTron-based multiplexer. Our model provides circuit designers with a tool to help understand the hTron's behavior during all design stages, thus promoting broader use of the hTron across various unexplored domains.

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Unconventional Ferroelectricity in Moiré Heterostructure

Z. Zheng, X. Wang, Z. Zhu, S. Carr, T. Devakul, S. C. de la Barrera, N. Paul, Z. Huang, A. Gao, Y. Zhang, D. Bérubé, K. N. Evancho, K. Watanabe, T. Taniguchi, L. Fu, Y. Wang, S.Y. Xu, E. Kaxiras, P. Jarillo-Herrero, Q. Ma
Sponsorship: CATS Program [6950173]

Electronic ferroelectricity represents a new paradigm in which spontaneous symmetry breaking is driven by electronic correlations, in contrast to traditional lattice-driven ferroelectricity, which results in the formation of electric dipoles. Due to its electronic nature, electronic ferroelectricity is expected to exhibit novel characteristics, such as ultrafast switching, large polarization, exceptional durability, and multiple polarization states. However, despite its fundamental interest and technological advantages, switchable electronic ferroelectricity remains exceedingly rare. This abstract will discuss our discovery of a novel electronic ratchet effect in a layer-contrasting graphene-boron nitride moiré heterostructure, which could serve as new evidence of switchable electronic ferroelectricity. Our engineered layer-asymmetric moiré potential landscapes result in a bipartite electronic system, in which we demonstrate a non-volatile ratcheting behavior tunable by gate voltages. Importantly, the memory states can be stabilized in a quasi-continuous fashion, exhibiting behavior markedly distinct from known ferroelectrics. Our experimental observations, simulations, and theoretical analysis suggest that dipolar excitons could be the driving force and elementary ferroelectric units in our system. This indicates a new type of electronic ferroelectricity where the formation of dipolar excitons with aligned moments generates a macroscopic polarization and leads to an electronically-driven ferroelectric response. Our result could pave the way for innovative quantum analog memory and synaptic devices.

Elucidating the Dominant Exciton Dynamics in MOCs through Physical, Chemical, and Electrical Manipulation of the Lattice

N. J. Samulewicz, W. S. Lee, W. A. Tisdale
Sponsorship: NSF Graduate Research Fellowship award no. 1745302, U.S Army Research Office award no. W911NF-23-1-0229

Rapidly expanding integration of semiconductors in consumer electronics up through large-scale supercomputers necessitates substantial quantum efficiency improvements to reduce global electricity consumption. 2D semiconductors, like transition metal dichalcogenides (TMDs) and 2D layered perovskites, have emerged in recent years as strong contenders over silicon and other bulk semiconductors due to their strong exciton binding energy and highly tunable properties.

Our lab investigates metal organic chalcogenolates (MOCs) as 2D semiconductors that can improve upon these existing structures—for example, the layer dependence of TMDs and instability of lead halide perovskites. MOCs are novel van der Waals stacked hybrid organic-inorganic semiconductors with extreme 1D quantum confinement, in-plane anisotropy, and layer independent emission. These properties are promising for applications as light emitting diodes (LEDs), excitonic switches, and a variety of other optoelectronic devices. Silver phenylselenolate, $[AgSePh]_\infty$, is a MOC of particular interest due to its narrow, naturally blue emission (~467 nm), along with its high environmental stability from covalently bonded organic and inorganic atoms. However, its excited state dynamics are still dominated by nonradiative recombination mechanisms, limiting its potential to revolutionize future semiconductor frameworks. This work details plans to perform physical, chemical, and electrical manipulation of MOCs to identify the influence of extrinsic defects and intrinsic material properties on exciton mobility and recombination in 2D hybrid semiconductors.

Universal Transferred Process for 2D Materials

S. He, Z. Hennighausen, J. Kong
Sponsorship: U. S. Army Research Laboratory and the U. S. Army Research Office under contract/grant number W911NF2320057

Two-dimensional (2D) materials have garnered significant attention due to their exceptional properties, but preparing with controllable thickness and usable surface area is still challenging. Numerous techniques have emerged for synthesizing high-quality and large-area 2D materials. Among these methods, chemical vapor deposition (CVD) has shown promise, offering superior control over film thickness and uniformity, making it a reliable technology for wafer-scale manufacturing. On the other hand, the typical wet transfer method using PMMA presents a potential solution for transferring 2D materials in large-scale. However, it faces limitations when transferring CVD-synthesized 2D materials from the growth substrate to the target substrate over large areas while maintaining clean surface. To overcome these challenges, we introduce a universal transfer process to keep clean surface using other polymers within a vacuum environment. Comparing wet-transfer and roll-to-roll transfer with vacuum dry transfer. Furthermore, we investigate the different surface situation of 2D materials using different polymers under atmospheric and vacuum environment. Our proposed method opens new possibilities for residue-free 2D materials on a large scale, with potential applications under diverse environments.

Defects Break the Self-Limiting Nature of the Room-Temperature Atomic-Layer Substitution for Growing Janus Monolayer Transition Metal Dichalcogenides

T. Zhang, X. Zheng, Y. R. Peng, K. Zhang, Y. Zhu, T. H. Yang, H. Liu, S. Y. Tang, Y. Guo, Y. L. Chueh, T. Cao, J. Kong
Sponsorship: US Department of Energy (DOE), Office of Science, Basic Energy Sciences under Award DE-SC0020042.

Janus monolayer transition metal dichalcogenides (J-TMDs) are gaining an increasing attention because of various intriguing properties that arise from their unique asymmetrical structure. A low-energy-barrier room-temperature atomic-layer substitution (RT-ALS) approach has recently been developed to obtain J-TMDs. This method reliably converts either MS_2 or MSe_2 (M represents a metal atom) into MSSe-type J-TMDs with controlled out-of-plane dipole orientations. Theoretical calculations based on a perfect monolayer TMD lattice model have illustrated that the RT-ALS reaction is self-limiting, in which only the topmost layer of chalcogen atoms is substituted. However, it remains unexplored how the atomic defects in monolayer TMDs affect the RT-ALS reaction pathway and the resulting J-TMDs' crystal quality.

Herein, we studied the role of defects on the RT-ALS process using high-quality and defect-rich $MoSe_2$, synthesized by a recently devised defect-engineered growth approach, as starting materials. Very interestingly, we found that an increased defect density in the starting material breaks the self-limiting nature of RT-ALS, leading to the incorporation of S in the bottom atomic layer of the as-synthesized Janus MoSeS. Our results indicate a positive correlation between the qualities of starting material and resulting J-TMDs, and suggest a defect-mediated atomic substitution pathway that has not been considered before. Our study contributes to the understanding and optimization of J-TMD preparation strategies to make these materials ready for constructing novel electronics, photonics, and Moiré heterostructures in the future.

Elucidating the Role of MOF Pore Size on OSN Performance of Microporous Polymer-based Mixed-matrix Membranes

W. Wu, T. H. Lee, G. Dovranova, A. Hernandez, Z. P. Smith
Sponsorship: ExxonMobil

Organic solvent-based separations are ubiquitous in the chemical industry, but they often rely on energy-intensive processes. Membrane technology provides an energy-efficient alternative to offset the energy cost. However, developing highly selective membranes for organic solvent nanofiltration (OSN) has been a significant challenge due to the poor stability of polymers under aggressive solvent conditions. Mixed-matrix membranes (MMMs) based on fillers such as metal–organic frameworks (MOFs) with well-defined porous structures have shown promise in overcoming these limitations. While material design efforts have improved OSN performance with MMMs, the fundamental mechanisms behind the effects of filler incorporation on solvent transport are not yet fully understood. In this study, we aim to elucidate the effects of MOF pore size on OSN performance for microporous polymer-based MMMs.

A series of MOF nanoparticles with similar chemistry but systematically increasing pore sizes (UiO-6x-NH_2 (x=6,7,8)) were chosen for this work. A carboxylic acid functionalized PIM-1 polymer (PIM-COOH) and the MOF nanoparticles were fabricated into thin-film MMMs using a newly developed spin-casting process followed by a crosslinking reaction. Dead-end permeation tests showed lower methanol permeability in all the MMMs compared to their polymer counterparts due to the restricted membrane swelling in the presence of MOF. The molecular weight cutoff (MWCO) of MMMs was probed through the permeation of dyes in methanol, revealing that the highest MWCO values were found for MMM samples with poor interfacial compatibility, indicating that unrestricted polymer swelling and defects need to be carefully controlled to enable MOF-based MMMs for OSN applications. For the MMMs with compatible interfaces, this study provides structure–property guidelines on the role of systematically increased MOF pore apertures and OSN separation performance.

Implementation of Multi-functional Diffractive Optical Elements by Implosion Fabrication

G. Yang, Q. Yang, Y. Salamin, Y. Kunai, T. Nambara, P. T. C. So, E, S. Boyden
Sponsorship: Fujikura

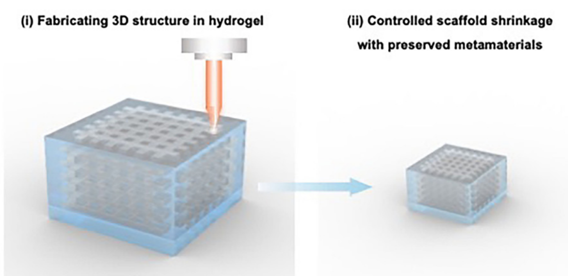
The development and integration of miniaturized holography and diffractive lenses represent an emerging field in optical technology. Nanofabrication technology plays a crucial role in enabling the design of optical systems at the nanoscale, facilitating the creation of structures and devices with unmatched precision and functionality. Despite this, current nanofabrication methods encounter challenges in crafting complex free-form three-dimensional (3D) structures and in constructing multi-layer, multi-level features at the nanoscale. We propose the use of implosion fabrication (ImpFab) to over-come these limitations, allowing the production of nano-optics that surpass the diffraction limits of direct laser writing (DLW) and enable the assembly of nano-precise, highly flexible 3D architectures.

In the ImpFab process (Figure 1), a hydrogel matrix undergoes selective photo-ablation in targeted areas using a two-photon laser, forming non-self-supporting 3D topological features. This matrix is then isotropically shrunk to achieve nano-precise features, essential for manipulating the critical refractive index (RI) differences required for advanced nanophotonics applications.

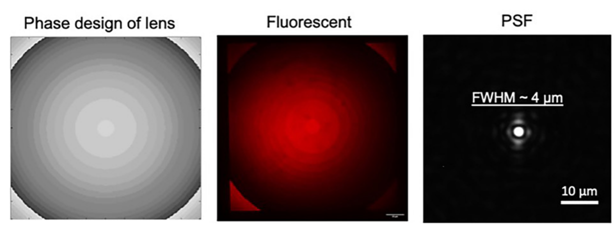
We initially constructed a Fresnel lens with three layers and four grayscale levels, achieving feature sizes as small as 200 nm laterally and 1 μm axially. The pre-shrinkage structures, visualized in the fluorescent images of Figure 2, closely correspond to the intended morphology and design patterns. Post-shrinkage, the lens retains detailed structural integrity. Performance evaluations through point spread function (PSF) testing confirmed that the focusing capabilities of the lens align with our design expectations.

Building on this, we developed a grayscale holographic device atop the lens layer. Illustrated in Figure 3, this device features a metasurface with a resolution of 100 nm, eight grayscale levels, and a step size of 200 nm, prominently displaying a simulated reconstruction of the MIT logo. Microscopic imaging of these metasurface nanostructures showed precise alignment with our design specifications. Far-field diffraction imaging tests of the holographic device revealed that it successfully diffracts light to reconstruct and project the encoded MIT logo pattern.

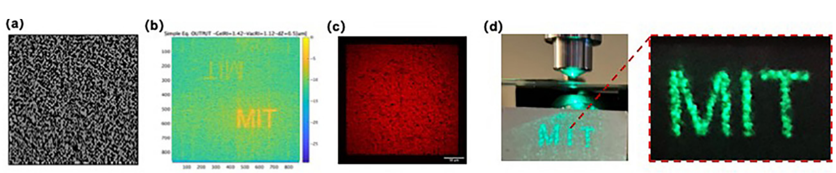
These demonstrations validate that ImpFab technology can achieve nanoscale optical integration. Ongoing advancements in ImpFab are paving the way for the integration of sophisticated, miniaturized optical elements such as holography and diffractive lenses, offering significant improvements in performance, efficiency, and application diversity. This technology effectively addresses the limitations of 3D nano-optics fabrication, heralding a new era in nanophotonics.



▲Figure 1: Fabrication process of nanoscale topological 3D structure in hydrogel scaffolds.



▲Figure 2: Diffractive lens design (left), fluorescent image of patterned structure (middle) and performance of PSF (right).



◀Figure 3: a) Designed mask of holographic metasurface; b) Simulated image of reconstructed MIT logo; c) Fluorescent image of plane of patterned layer; d) Far-field diffraction effect, displayed as MIT logo.

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Large Quantum Anomalous Hall Effect in Spin-orbit Proximitized Rhombohedral Graphene

T. Han, Z. Lu, Y. Yao, J. Yang, J. Seo, C. Yoon, K. Watanabe, T. Taniguchi, L. Fu, F. Zhang, L. Ju
Sponsorship: Sloan Fellowship, NSF

In 1988, Haldane proposed a prototype model to realize quantized Hall conductance in the ab-sence of a magnetic field. The model has informed the theoretical and experimental explora-tion of topological phases of matter for more than three decades. Although the Berry curvatures of the Haldane model have been demonstrated in a cold-atom experiment, the quantum anomalous Hall effect (QAHE), as the most prominent macroscopic signature of the Haldane model, could not be measured there. In solid-state systems, the QAHE has been observed in two categories of materials. The first is magnetic topological insulators such as Cr-/V doped $(Bi,Sb)_2Te_3$ and intrinsic $MnBi_2Te_4$, where the time-reversal-symmetry is broken by the ordering of magnetic elements and the Berry curvatures of the two valleys of opposite surfaces add up to a Chern number of 1. The second is two-dimensional materials with moiré superlattices at non-zero charge densities that correspond to odd filling factors, where the exchange interactions spontaneously break the time-reversal-symmetry and the Chern number arises from a single principal valley. Without the stacking of multiple (effectively decoupled) periods of molecular-beam-epitaxy-grown quantum wells in the vertical direction, the largest Chern number that has been realized so far is 2 in ferromagnetic systems that were not fully quantized at zero magnetic field. Is it possible to realize the QAHE without magnetic elements or moiré engineering? Can we get a larger Chern number in other QAHE systems? Such possibilities have remained elusive experimentally, although an integer QAHE in rhombohedral graphene was predicted to be possible by theory.

We report the QAHE in a rhombohedral pentalayer graphene/monolayer WS_2 hetero-structure. Distinct from other experimentally confirmed QAHE systems, this system has neither magnetic element nor moiré superlattice effect. The QAH states emerge at charge neutrality and feature Chern numbers $C = \pm 5$ at temperatures up to about 1.5 K. This large QAHE arises from the synergy of the electron correlation in intrinsic flat bands of pentalayer graphene, the gate-tuning effect, and the proximity-induced Ising spinorbit-coupling. Our experiment demonstrates the potential of crystalline two-dimensional materials for intertwined electron correlation and band topology physics and may enable a route for engineering chiral Majorana edge states.

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Neuromorphic Devices & AI Hardware Accelerators

Secure Digital In-memory Computing for Privacy and Integrity

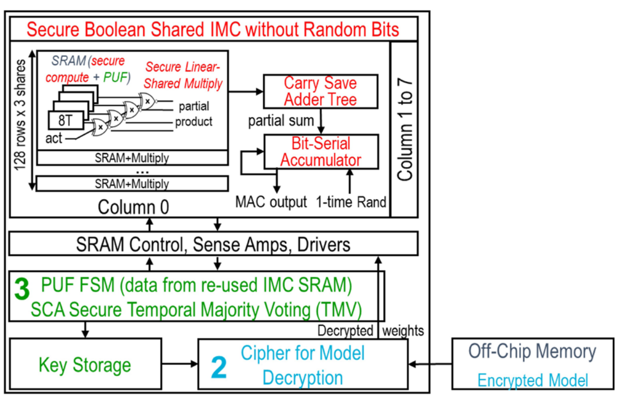
M. Ashok, S. Maji, X. Zhang, J. Cohn, A. P. Chandrakasan
Sponsorship: MIT-IBM Watson AI Lab, NSF Graduate Research Fellowship Program (Grant No. 1745302), MathWorks Engineering Fellowship

Machine learning accelerators are used in a wide variety of applications to achieve high energy efficiency at the expense of generalization. One specific architecture, digital in-memory compute (IMC), reduces data transfer energy by interleaving compute and memory while still targeting high accuracy, even with technology scaling.

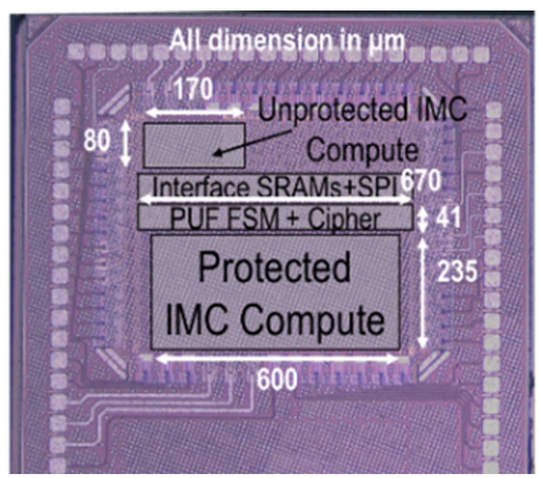
The security of these accelerators is essential to protect both the inputs and model. The input activations often reflect private data collected on a sensor, such as face images. The weights reveal information about private training datasets, which can be used to mount adversarial attacks. Two types of passive attacks can help an attacker gain this information: side channel attacks (SCAs), which correlate the integrated circuit's (IC) power consumption or electromagnetic missions to the data, and bus probing attacks (BPAs), which directly tap the traces between the IC and off-chip memory.

We propose addressing these security threats through an IMC macro with three key protections. The computation is split up into random shares, such that the total power consumption is uncorrelated to the data. By targeting practical attacker scenarios, this architecture is designed to eliminate the need for fresh random bits while minimizing area and energy overheads when possible. In addition, a National Institute of Standards and Technology standard lightweight cipher is included locally so that the model is present only in an encrypted form off-chip. Finally, a feedback-cut physical unclonable function that takes advantage of manufacturing variations in existing IMC memory is designed to generate secret keys on-chip.

With a combination of these contributions, we achieve a secure IMC macro in 14-nm complementary metal-oxide semiconductor (CMOS) technology. The design does not require any random number generators and has no limitations on neural network accuracy, providing a generalized solution for privacy and integrity in a variety of machine learning applications.



▲Figure 1: Proposed secure digital in-memory compute macro architecture with 3 key contributions (Boolean shared compute for SCA security, model decryption on-chip for BPA security, and secret key generated on-chip) highlighted.



▲Figure 2: Die micrograph of proposed protected and baseline unprotected macros in 14-nm CMOS technology. Key blocks and dimensions are noted.

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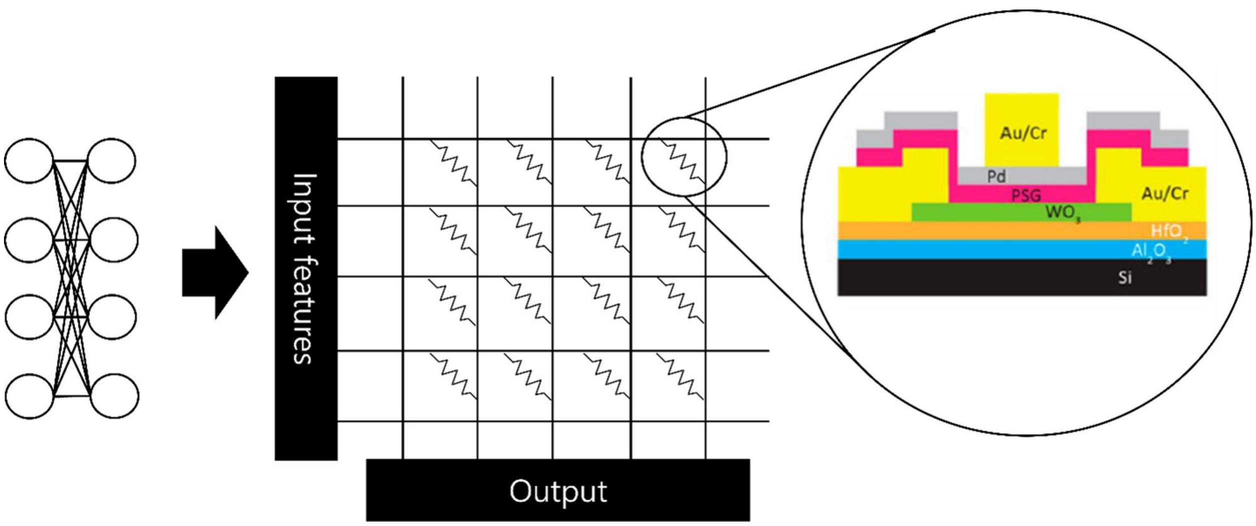
Analog In-memory Computing with Protonic Synapses

J. Lee, J. A. del Alamo
Sponsorship: IBM Watson

Though demand for computation in neural networks is skyrocketing, conventional computing resources are still constrained by their limited energy efficiency. One of the most promising solutions to this is analog in-memory computing (AIMC). In AIMC, synaptic weights of neural networks are encoded into the conductance of devices which are then configured into crossbar-arrays that perform the matrix-vector multiplication operation. Recently, protonic synapses were demonstrated with suitable properties for AIMC such as linear and symmetric conductance modulation. To study this, we have built a simulation model for protonic synapses and simulated a crossbar-array operation using IBM's AIHWKIT. AIMC with protonic synapses showed 97.1% accuracy in MNIST classification with a linear-4-layer network. This is comparable to a digital chip accuracy of 98%. We also tested the Tiki-taka algorithm that compensates for device non-idealities and identified the relation between the conductance modulation shapes and the performance of algorithm.

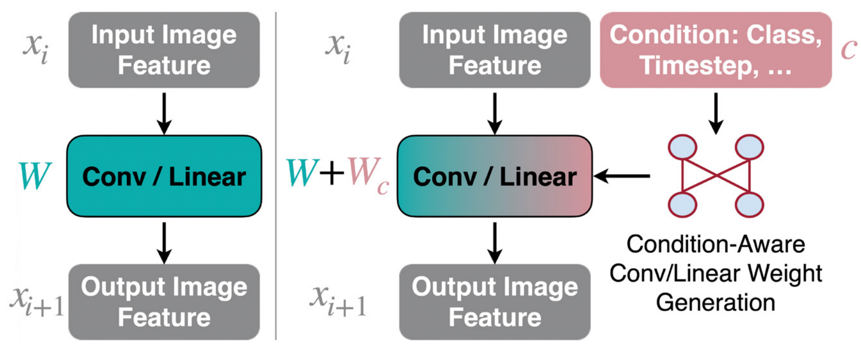


▲ Figure 1: Schematic of cross-bar array with protonic synapses.

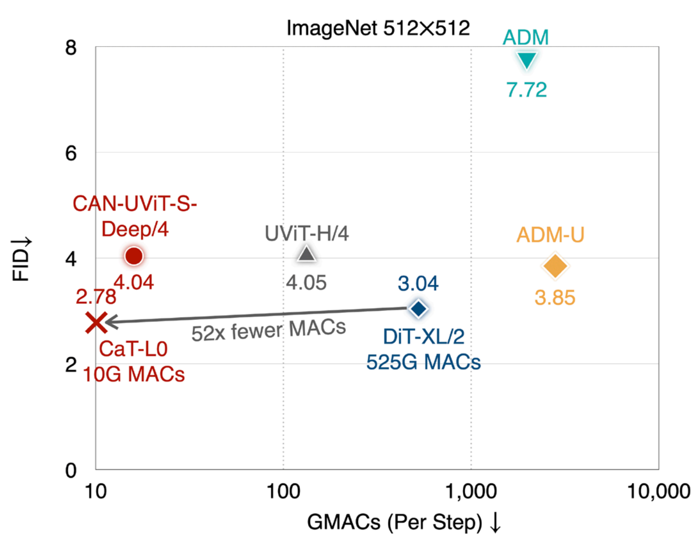
Condition-aware Neural Network for Controlled Image Generation

H. Cai, M. Li, Z. Zhang, Q. Zhang, M.-Y. Liu, S. Han
Sponsorship: MIT-IBM Watson AI Lab, Amazon, MIT Science Hub, NSF

We present Condition-Aware Neural Network (CAN), a new method for adding con-trol to image-generative models. In parallel to prior conditional control methods, CAN controls the image-generation process by dynamically manipulating the weight of the neural network. This is achieved by introducing a condition-aware weight generation module that generates conditional weight for convolution/linear layers based on the input condition. We test CAN on class-conditional image gen-eration on ImageNet and text-to-image generation on COCO. CAN consistently de-livers significant improvements for diffusion transformer models, including DiT and UViT. In particular, CAN combined with EfficientViT (CaT) achieves 2.78 FID on ImageNet 512x512, surpassing DiT-XL/2 while requiring 52x fewer MACs per sampling step.



▲Figure 1: Illustration of CAN.



◀Figure 2: Comparing CAN models and prior image-generative models on ImageNet 512X512.

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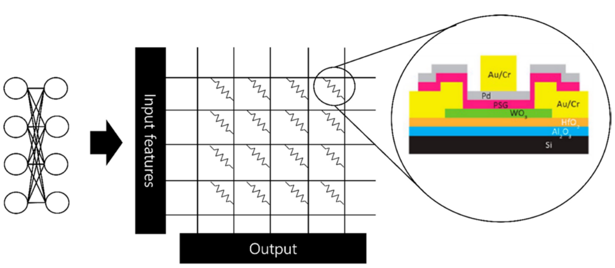
- H. Cai, et al. "EfficientViT: Multi-Scale Linear Attention for High-Resolution Dense Prediction," *Proc. IEEE/CVF International Conference on Computer Vision*, p. 2023.

IBM AIHWKIT Simulations of Analog Training Accelerators Based on Protonic Synapses

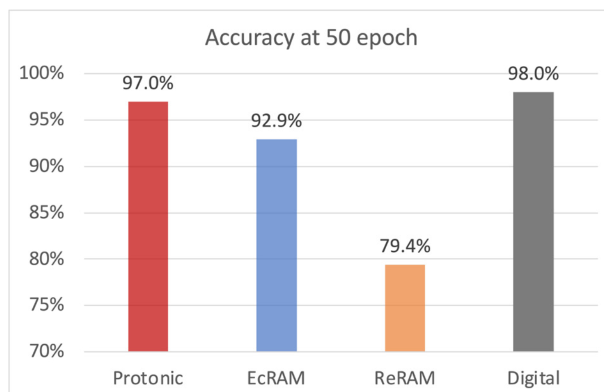
J. Lee, J. A. del Alamo
Sponsorship: IBM, Ericsson

Though demand for computation in neural networks is skyrocketing, conventional computing resources are constrained by their limited energy efficiency. One of the most promising solutions to this is analog in-memory computing (AIMC). In AIMC, synaptic weights of neural networks are encoded into the conductance of devices that are then configured into crossbar-arrays that perform the matrix-vector multiplication operation. Recently, our group demonstrated protonic synapses with suitable properties for AIMC such as linear and symmetric conductance modulation. To study the potential of this new device technology for AIMC, we are carrying out simulations of crossbar-array operation using IBM's AIHWKIT.

With AIHWKIT, users can simulate AIMC accelerators and observe how modifying the device properties directly affects the performance of neural networks. Additionally, the tool enables the evaluation of performance in various types of neural networks, including convolutional neural networks, LSTM, Transformer, and others, which are currently under extensive research. Further, this system can also investigate the performance of different algorithms, such as stochastic gradient descent (SGD), Tikitaka, etc. In our studies, we compare MIT's protonic synapses against other analog synaptic devices such as IBM's ReRAM and ECRAM technologies. We demonstrate an accuracy of our protonic devices of 97.0% in Modified National Institute of Standards and Technology (MNIST) hand-written digit image classification using SGD, which is much higher than with ReRAM of 79.4%. Protonic device accuracy approaches that of digital circuits, which typically reach 98%. This enhancement in performance is due to the more symmetric and linear modulation of weights in protonic synapses. Our research is investigating the effect of device non-idealities on accuracy and testing several analog computing algorithms designed to mitigate their degrading impact.



▲Figure 1: Schematic of cross-bar array for neural network with protonic synapses; input features are loaded in analog voltages from left side, and output emerges from bottom. Each crosspoint has a protonic synapse.



▲Figure 2: Comparison of accuracy of 4-layer analog neural networks based on different device technologies after training with MNIST model. For reference, result of digital network is also shown.

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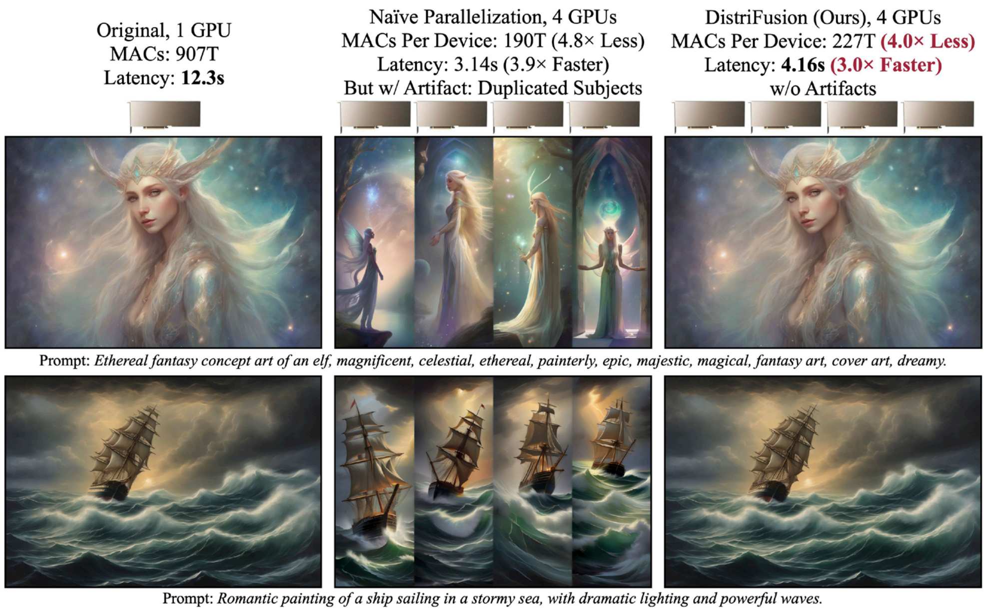
DistriFusion: Distributed Parallel Inference for High-resolution Diffusion Models

M. Li, T. Cai, J. Cao, Q. Zhang, H. Cai, J. Bai, Y. Jia, M.-Y. Liu, K. Li, S. Han
Sponsorship: MIT-IBM Watson AI Lab, Amazon, MIT Science Hub, NSF

Diffusion models have achieved great success in synthesizing high-quality images. However, generating high-resolution images with diffusion models is still challenging due to the enormous computational costs, resulting in a prohibitive latency for interactive applications. In this paper, we propose DistriFusion to tackle this problem by leveraging parallelism across multiple graphic processing units (GPUs). Our method splits the model input into multiple patches and assigns each patch to a GPU. However, naively implementing such an algorithm breaks the interaction between patches and loses fidelity while incorporating such an interaction will incur tremendous communication overhead. To overcome this dilemma, we observe the high similarity between the input from adjacent diffusion steps and propose displaced patch parallelism, which takes advantage of the sequential nature of the diffusion process by reusing the pre-computed feature maps from the previous timestep to provide context for the current step. Therefore, our method supports asynchronous communication, which can be pipelined by computation. Extensive experiments show that our method can be applied to recent Stable Diffusion XL with no quality degradation and achieve up to a 6.1× speedup on eight A100 GPUs compared to one.



▲Figure 1: We introduce DistriFusion, a training-free algorithm to harness multiple GPUs to accelerate diffusion model inference without sacrificing image quality. Naive Patch suffers from the fragmentation issue due to the lack of patch interaction. Our DistriFusion removes artifacts and avoids the communication overhead by reusing the features from the previous steps. Setting: SDXL with 50-step Euler sampler, 1280×1920 resolution. Latency is measured on A100s.

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A Massively Parallel In-memory-computing Architecture Using Stochastic Computing

Q. Wang, B. C. McGoldrick, M. A. Baldo, L. Liu
Sponsorship: SRC, Mathworks

The potential of in-memory computing (IMC) to circumvent the inefficiencies of traditional computing architectures has been widely recognized in the field of machine learning. Despite this potential, current IMC models are hampered by the difficulty of embedding complex arithmetic operations on-site, and the lack of capability for large-scale yet versatile parallel computation, which significantly diminish the applicability of IMC in scenarios demanding high computational throughput and intricate mathematical processing. Confronting these limitations, the research introduces a novel IMC architecture that utilizes stochastic MTJs to streamline in-memory operations. Beyond mere energy and space efficiency, this architecture innovates with a hierarchical approach that emulates the structure of biological neural networks, offering a solution to the scalability challenge. Within this hierarchy, local computations are performed by densely connected neuron-like nodes, enabling rapid data processing and communication for simpler tasks. Meanwhile, more complex and distant interactions are managed via a Network on Chip (NoC), facilitating efficient communication across the larger neural network. This dual-level organization allows for both intensive local computation and broader inter-neuron communication, effectively mirroring the parallelism and connectivity of the brain, and unlocking new potentials for IMC in supporting sophisticated and large-scale parallel machine learning workloads.

Tailor Swiftiles: Accelerating Sparse Tensor Algebra by Overbooking Buffer Capacity

Z. Y. Xue, Y. N. Wu, J. S. Emer, V. Sze
Sponsorship: MIT AI Hardware Program

Tensor algebra describes a class of applications that are increasingly being used in fields such as machine learning, data science, graph analytics, scientific simulations, and engineering modeling. Although many of these applications operate on tensor data that has very high sparsity (i.e., many zeros), exploiting this sparsity to save both computation and memory is challenging. Prior sparse tensor algebra accelerators have explored splitting tensors into tiles to increase exploitable data reuse and improve throughput, but typically allocates tile size in a given buffer for the least sparse tile and thus limits utilization of available memory resources when sparsity varies between different regions of a tensor.

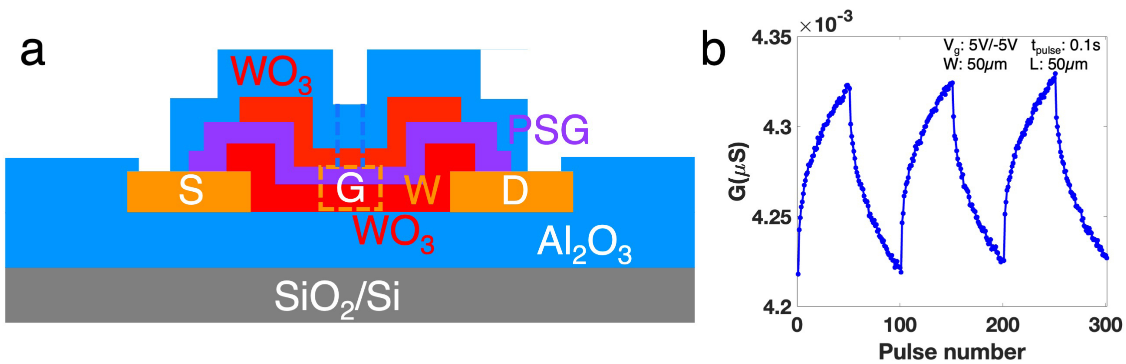
This paper proposes a speculative tensor tiling approach, called overbooking, to improve buffer utilization by taking advantage of the distribution of nonzero elements in sparse tensors to construct larger tiles with greater data reuse. We propose a low-overhead hardware mechanism, Tailors, that can tolerate data overflow by design while ensuring reasonable data reuse and introduce a statistical tiling approach, Swiftiles, that ensures high buffer utilization by picking a tile size so that tiles usually fit within the buffer's capacity, but can potentially overflow, i.e., it overbooks the buffers. Across a suite of 22 sparse tensor algebra workloads, we show that our proposed overbooking strategy introduces an average speedup of 52.7x and 2.3x and an average energy reduction of 22.5x and 2.5x over an existing sparse tensor algebra accelerator without and with optimized tiling, respectively.

Symmetric PSG/WO3 Protonic Synapses for Analog Deep Learning

D. Shen, J. A. del Alamo
Sponsorship: MIT-IBM Watson AI Lab

To solve the overcoming computational bottlenecks for deep learning, analog deep learning accelerators process information locally with specific devices for matrix multiplication calculations and outer product updates. Among them, electrochemical RAMs modulate channel resistance by ionic exchange between the channel and a gate reservoir via an electrolyte.

This study focuses on proton-based ionic synapses featuring in-situ protonated H_xWO_{3-x} as both channel and gate reservoir, and phosphorus-doped silicon dioxide (PSG) as electrolyte. This design aims to enable neural network training with enhanced energy efficiency, non-volatility, and low latency. We have experimentally implemented this design in a CMOS and back-end-of-line compatible process. Our protonic synapse with a vertically symmetric structure enables non-volatile and repeatable channel conductance modulation under voltage pulses across gate and channel, thus showing promising applications in deep learning accelerators.



▲Figure 1: (a) Schematic of symmetric WO_3-based protonic synapse with tungsten contacts, PSG electrolyte and Al_2O_3 encapsulation, fabricated in a lift-off-free and in-situ protonation process. (b) Conductance modulation under voltage pulses shows repeatable control.

Analysis of Memristor Device Requirements and Update Thresholding Strategy for Precision Programming of Neuromorphic Memristor Arrays

G. Lee, J. Kim

Neuromorphic computing, inspired by neural systems, presents advantages such as minimized data transmission, reduced power consumption, and parallel computation, spanning applications in artificial intelligence (AI), scientific computing, and security. Neuromorphic computing, specifically with a memristor crossbar array, shows promise as an AI inference accelerator, demonstrated through on-chip deep neural network inferences comparable to software-based methods. Despite the prevalent one-transistor one-resistor (1T1R) system ensuring precise memristor programming and overcoming sneak path issues, it compromises power, speed, and design simplicity. For these reasons, the simplest one-resistor (1R) system that can accurately program memristors and minimize the sneak path problem would be the ultimate solution. However, precise conductance adjustments at cross-points remain challenging due to asymmetry, poor selectivity, sneak paths, and stochasticity.

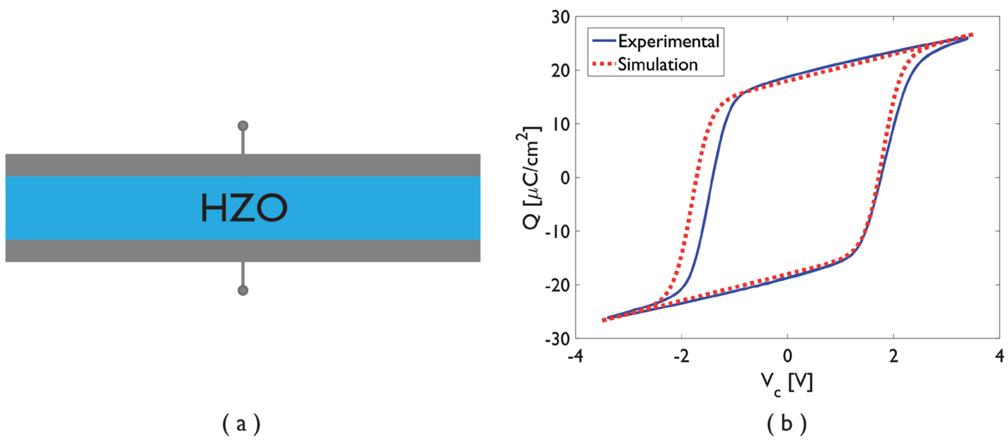
This study introduces the simplest automatic programming algorithm, employing iterative conductance reads and updates. It analyzes memristor requirements for high programming accuracy, establishing relationships with array size and parameters like interconnect-to-memristor conductance ratio. Selectivity is identified as enhancing convergence speed. Notably, update asymmetry hampers programming, which is addressed by an update event thresholding algorithm, significantly improving accuracy. This analysis and programming strategy hold the potential to aid the 1R memristor array system in overcoming programming challenges, realizing an ideal AI inference accelerator.

Large-signal TCAD Simulation of Polarization Switching in Ferroelectric Devices

J. Navarro, Y. Shao, J. A. del Alamo
Sponsorship: Technical University of Madrid (UPM), Semiconductor Research Corporation

Ferroelectric materials enjoy spontaneous and non-volatile charge polarization with an orientation that can be switched by the application of a voltage. Recently, the discovery of ferroelectricity in HZO ($Hf_{0.5}Zr_{0.5}O_2$) thin films, compatible with current CMOS fabrication processes, have made ferroelectric field-effect transistors (FE-FETs) attractive as low power, nonvolatile memory devices for neuromorphic computing. However, the physics behind HZO polarization switching, especially in FE-FETs, are not widely understood.

In this work, we carry out TCAD simulations on FE capacitors and FE-FETs under large-signal operation. We have employed the Preisach model to reproduce the experimental polarization-voltage hysteresis loop, including transient behavior for low-frequency signals. Currently we are studying the nonvolatile memory behavior in FE-FETs. These results allow us to study how current physical models differ from experimental data, providing insights on the essential FE physics.

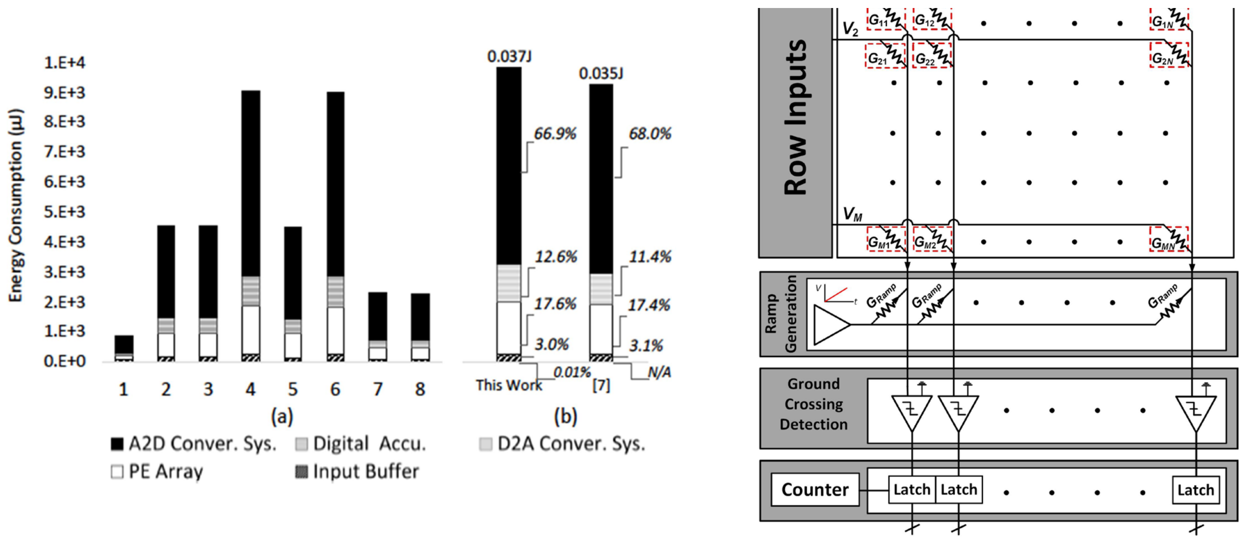


▲Figure 1: (a) FE Capacitor structure (MFM) and (b) experimental and simulated polarization-voltage (P-V) hysteresis loops

Interface Circuits for Analog In-Memory Computing

M. A. G. Elsheikh, H.-S. Lee
Sponsorship: MIT/MTL Samsung Semiconductor Research Fund

Machine learning (ML) has found its way into our daily lives in applications including image processing, voice recognition and healthcare. The energy and speed bottlenecks in ML stem from data movement back and forth between the memory and the processing element. Analog compute in-memory (CIM) presents an alternative where the processing is done locally within the memory, and the analog nature of it allows the parallelization of a significant number of multiply-and-accumulate operations. However, current read-out circuits of CIM circuits are energy and area hungry leading a slow-down and energy inefficiency in the overall accelerator performance. In this work, we proposed a new design for interface circuits using single-slope analog to digital converters that exploit the typical statistics of neural network outputs to optimize speed and efficiency. This paves the way for the incorporation of CIM accelerator in low-power applications such as health monitoring and mobile applications.



▲ Figure 1: (a)Energy breakdown in analog CIM systems (b) proposed single-slope analog to digital converter readout circuits for analog CIM

Sub-Nanometer Interface Modifications for Conductance Modulation in Proton-Based ECRAM Devices

J. Meyer, M. Huang, B. Yildiz
Sponsorship: DoD NDSEG Fellowship (2022 Fellow), DOE EFRC Hydrogen in Energy and Information Sciences (HEISs)

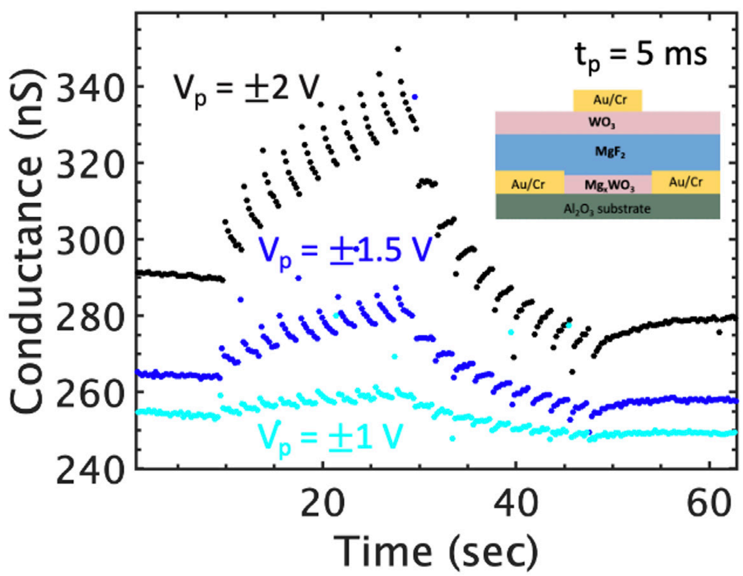
Three-terminal electrochemical random-access memory (ECRAM) devices have gained interest for use as resistive elements in energy-efficient neuromorphic computing architectures. ECRAM devices display promising non-volatility, reversibility, and symmetric switching operations through solid-state ion intercalation of a channel material, typically WO_3. However, these devices remain limited in energy-efficiency and programming speed, displaying operating voltages above 1 V and programming on the order of microseconds. Advances in thin high ionic conductivity electrolytes have decreased the operating voltage required for switching, but as electrolyte thickness approaches a few nanometers, other optimizations are required.

The structure of ECRAM devices is similar to solid-state lithium-ion batteries, for which electrode-electrolyte interfaces can be significant impedances to ion transport. For proton-based ECRAM, much less is known about proton transport across solid-state interfaces. This work chemically modifies the electrolyte-channel interface in a proton-based ECRAM device with sputtered metals and metal oxides. Differences in conductance modulation across interface-modified devices are presented. Surface-modified WO_3 films are examined with X-ray photoelectron spectroscopy. An electrochemical impedance spectroscopy setup is also used to separate the impedance contributions of electrolyte and interface in the devices. In doing so, we demonstrate some tunability of ECRAM device operation with sub-nanometer interface modifications. These results suggest modifying the electrolyte-channel interface in ECRAM devices may be another route to achieve faster neuromorphic computing with lower operating voltages.

Magnesium Fluoride as a Thin Film Electrolyte in Mg-based Electrochemical Ionic Synapse (EIS) Devices

M. L. Schwacke, J. A. del Alamo, J. Li, B. Yildiz
Sponsorship: Semiconductor Research Corporation (Task ID: 3010-001), MIT Quest

Dynamic doping by electrochemical ion intercalation is a promising mechanism for modulating electronic conductivity, allowing for energy-efficient, brain-inspired computing hardware. Programmable resistors which operate by this mechanism are called electrochemical ionic synapses (EIS). Use of Mg^{2+} as the working ion in EIS allows for both low energy consumption (compared to O-EIS) and good retention in ambient air (compared to H-EIS). However, while Mg-EIS devices based on organic electrolytes have provided a promising proof-of-concept; inorganic, thin film Mg electrolytes are needed for compatibility with CMOS processing. Here we report development of MgF_2 as a thin film electrolyte for Mg-EIS. We investigate how deposition technique (RF sputtering, electron beam evaporation) affects the MgF_2 film properties and by extension device characteristics. We show that Mg-EIS with MgF_2 electrolyte films are promising for CMOS-compatible EIS with long-term retention and low energy consumption.



▲ Figure 1: Channel conductance of Mg-EIS device with MgF_2 electrolyte (schematic shown in inset) in response to 10 positive followed by 10 negative voltage pulses.

Polaronic Carrier Mobility in Channel Materials for CMOS-compatible ECRAM

P. Žguns, B. Yildiz
Sponsorship: SRC JUMP 2.0 SUPREME Center

Neuromorphic computing hardware based on electrochemical random access memory (ECRAM) enables low-energy computing and nanosecond timescale operation [1–3]. In these devices, the electrochemical intercalation of hydrogen modulates the electronic conductivity of the channel material, where high sensitivity of conductivity to hydrogen insertion is needed for high energy efficiency. Therefore, to select promising channel materials, the impact of hydrogen on carrier mobility needs to be understood. Here, we computationally study hydrogenated, CMOS-compatible channel materials H_xWO_3, $H_xV_2O_5$, and H_xMoO_3. We apply the DFT+*U* method to describe the electronic structure and polaron localization in the host oxide lattice. We identify the ground state configurations of the proton–polaron pairs and probe microscopic factors that control polaron mobility, viz. the polaron migration barriers in pristine lattice and proton–polaron association energy (i.e., the energy required to break the pair). The polaron migration barriers are comparable to the polaron–proton association energies (which are on the order of 0.1 eV–0.2 eV), highlighting that the attraction between polarons and protons plays an important role in polaron mobility. These computational findings will help us to identify the most suitable CMOS-compatible oxide channel material for low-power ECRAM devices for neuromorphic computing applications.

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Analog Complex-valued Neural Networks for Quadratic Energy Savings

M. G. Bacvanski, S. K. Vadlamani, D. R. Englund
Sponsorship: NSF RAISE-TAQS (1936314), NSF C-Accel (2040695), NTT Research Inc.

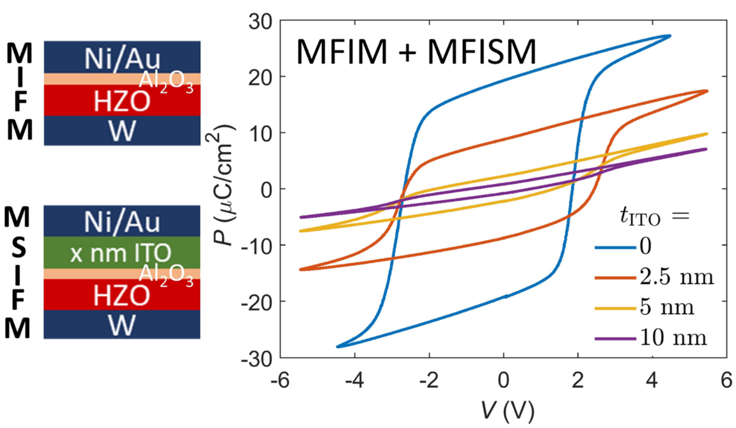
Neural networks (NNs) that are composed of complex weights and operate over complex inputs have demonstrated excellent performance in domains like medical data and signal processing because of their natural ability to manipulate phase and amplitude. However, implementing these complex-valued NNs on conventional digital GPU hardware entails performing several times more multiplication and addition operations than real-valued NNs of the same size. In this work, we propose an AI accelerator that uses standard telecommunications hardware to efficiently implement complex-valued NNs by combining standard modulation schemes with homodyne detection. Through extensive numerical experiments, we demonstrate that these telecom-based analog NNs perform identically to traditional real-valued neural networks on several standard real-valued datasets, while consuming quadratically lower amounts of energy.

CMOS-compatible Ferroelectric Memory for Analog Neural Network Accelerators

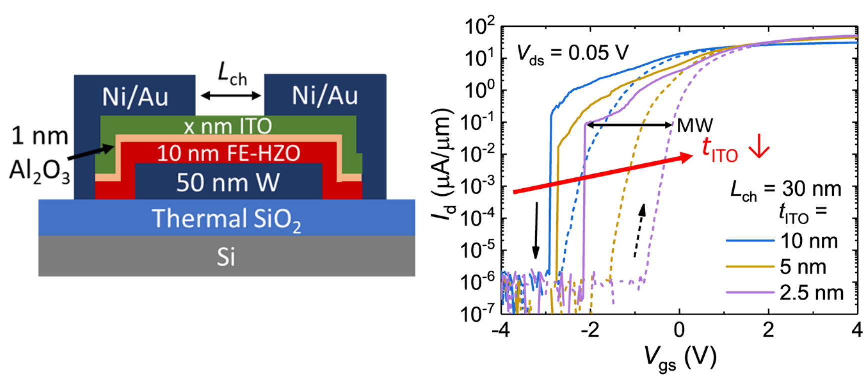
Y. Shao, E. R. Borujeny, T. Kim, T. E. Espedal, J. C.-C. Huang, J. Navarro, D. A. Antoniadis, J. A. del Alamo
Sponsorship: Intel Corporation, SRC

Artificial intelligence has irreversibly changed the way information is stored and processed. However, the huge energy consumption and enormous computation time required for training modern deep learning models highlights the urgent need for energy- and time-efficient hard-ware uniquely designed to implement AI algorithms. Recently, analog computing has been proposed as an alternative to the digital counterpart. In an analog neural network accelerator, core computations are carried out in the analog domain, exploiting unique device properties and fundamental physical laws.

In this work, we examine the potential of complementary metal-oxide semiconductor- (CMOS) compatible ferroelectric field-effect transistors (FE-FETs) with a metal-oxide channel as the core device for analog accelerators. Extensive electrical characterizations, including large-signal polarization-voltage (P-V), small-signal capacitance-voltage, and direct-current current-voltage characteristics have been carried out on multiple device structures. We have found that the thickness scaling of the channel material, i.e., indium-tin-oxide (ITO) in our study, plays a key role in the enhancement of FE polarization switching (Figure 1). To scale down ITO thickness for better device performance, we studied thin-film transistors with ITO channel thickness down to 2.5 nm and obtained a field-effect mobility of 34 cm²/V·s in 2.5-nm-thick ITO films. In addition, we designed and fabricated FE-FETs with highly scaled channel length and source/drain contact length in a back-gate configuration. Thanks to the scaled ITO thickness, we observed a large memory window of ~2 V (Figure 2), which is among the best reported in the literature. On the other hand, the speed of FE polarization switching in the transistors/synapses, which determines the operation frequency of the analog crossbar array, is of great importance. In our fabricated devices, preliminary results show that sub-microsecond FE polarization switching could be obtained. These results pave the way to the realization of CMOS-compatible ferroelectric programmable resistors for analog accelerator arrays.



◀ Figure 1: P-V loops of metal/FE-HZO/insulator/metal and metal/FE-HZO/insulator/semiconductor/metal structures with different ITO thicknesses.



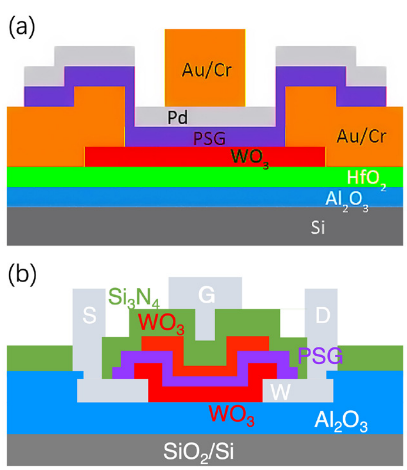
▶ Figure 2: FE-FET structure (left) and subthreshold characteristics of devices with different ITO thicknesses (right). Memory window is defined at 100 nA/μm.

Device Stack Optimization for Protonic Programmable Resistors

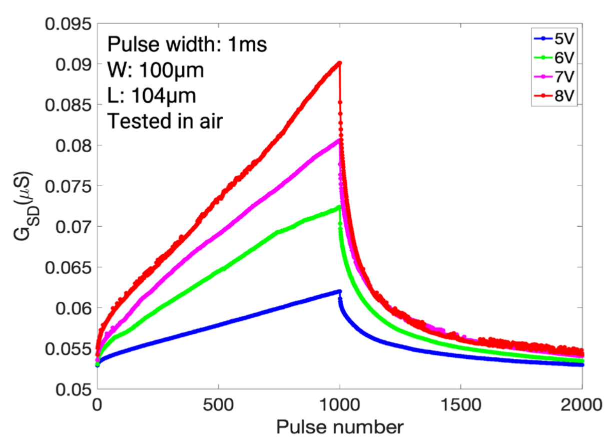
D. Shen, J. A. del Alamo
Sponsorship: MIT-IBM Watson AI Lab

Analog computing offers a potential solution for over-coming computational bot-tlenecks in traditional digi-tal systems utilized for deep learning. The fundamental con-cept of analog deep learning accelerators involves processing information locally by leveraging the phys-ical properties of devices, rather than conventional Boolean arith-metic—specifically, using Ohm's and Kirchhoff's laws for matrix inner product calcula-tions and threshold-based updating for the outer product. Among various physical principles, electrochemical ion-intercalation makes possible a three-terminal de-vice with a channel resistance that is modulated by ionic exchange between the channel and a gate reser-voir via an electrolyte. This study focuses on such ion-ic programmable resistors featuring WO_3 as a channel and protons as the working ions, aiming to pro-vide information processing with increased energy savings, non-volatility, and low la-tency. Our group's previous work, with a device structure shown in Figure 1a, has demonstrated Si-compatible nanoscale devices that are 1,000 times smaller than bio-logical neurons, enabling channel conductance modulation over a 20x range with na-nosecond operation at room temperature.

In this work, we have optimized the device stack in four directions and used nano-porous phosphosilicate glass (PSG) to demonstrate a symmetric WO_3-PSG-WO_3 structure in a complementary metal-oxide semiconductor- (CMOS) compatible and lift-off-free process, with the help of a circular transfer length method, which efficiently ex-amines the resistance properties of WO_3. We have explored: (a) device protonation as part of the fabrication process, (b) encapsulation preventing proton depletion during device fabrication and operation, (c) contact metal optimization to replace gold with a CMOS-compatible material, and (d) a PSG evaluation vehicle to optimize device per-formance. Putting it all together, we have designed and fabricated a symmetric device, shown in Figure 1b, which enables non-volatile and repeatable channel conductance modulation under voltage pulses across gate and channel with results shown in Fig-ure 2, thus showing promising application in deep learning accelerators.



▲ Figure 1: WO_3 protonic device structures: (a) original device structure with WO_3 as channel, PSG as electro-lyte, and Pd as hydrogen reservoir and controlling gate. (b) Optimized symmetric device structure with W as contact metal, in-situ protonated WO_3 as both channel and gate reservoir, and Si_3N_4 as encapsulation.



▲ Figure 2: Conductance modulation curve for different voltage pulses of a symmetric device. The device shows linear conductance increase with positive pulses on gate. With encapsulation and in-situ protonation, the device can repeatably modulate its conductance under air.

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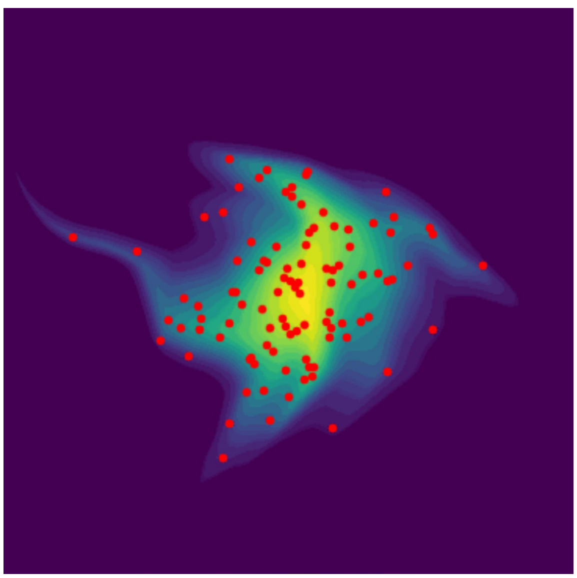
The Use of Cross-validation in Semi-supervised Anomaly Detection

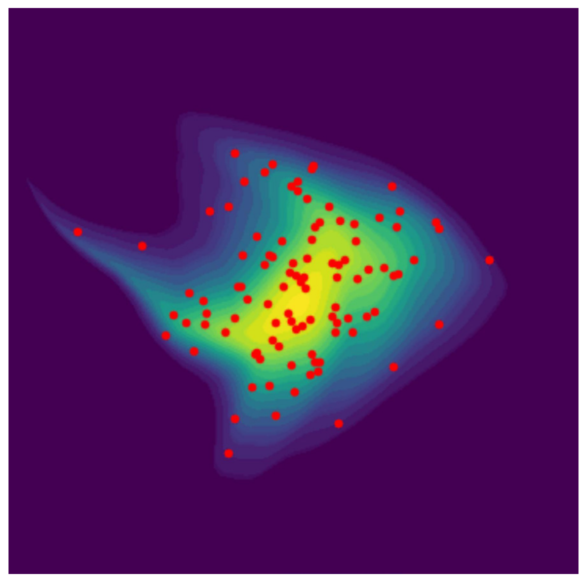
F.-K, Sun, D. S. Boning
Sponsorship: Analog Devices

Unplanned industrial downtime can result in significant financial losses and operational disruptions. To address these issues, companies are investing in sensors designed to detect anomalies and reduce downtime. However, anomaly detection is challenging because anomalies are rare. Anomaly detection algorithms are typically developed assuming that only known good data are used for training and anomalies will only occur during inference. These assumptions can lead to overfitting, where an algorithm performs well on the training set but poorly during actual use.

In this work, we propose using a validation set to help regularize and reduce overfitting. With a random training-validation split, ideally, the losses on both sets should be similarly distributed. However, due to the expressiveness of neural networks, we often see the training set loss continuously decrease while the validation set loss decreases only moderately or even increases, leading to overfitting. We suggest matching the loss distributions from the training and validation sets using the Kolmogorov–Smirnov (KS) statistic. Since the KS statistic is originally non-differentiable, we designed a sigmoid-smoothed version to enable gradient descent. Additionally, we propose randomly splitting the training and validation sets each epoch, allowing the model to train on all data samples. Our techniques result in smoother decision boundaries and better generalization across various datasets, as demonstrated in the following results.



▲Figure 1: An example showing the decision boundary without using a validation set.

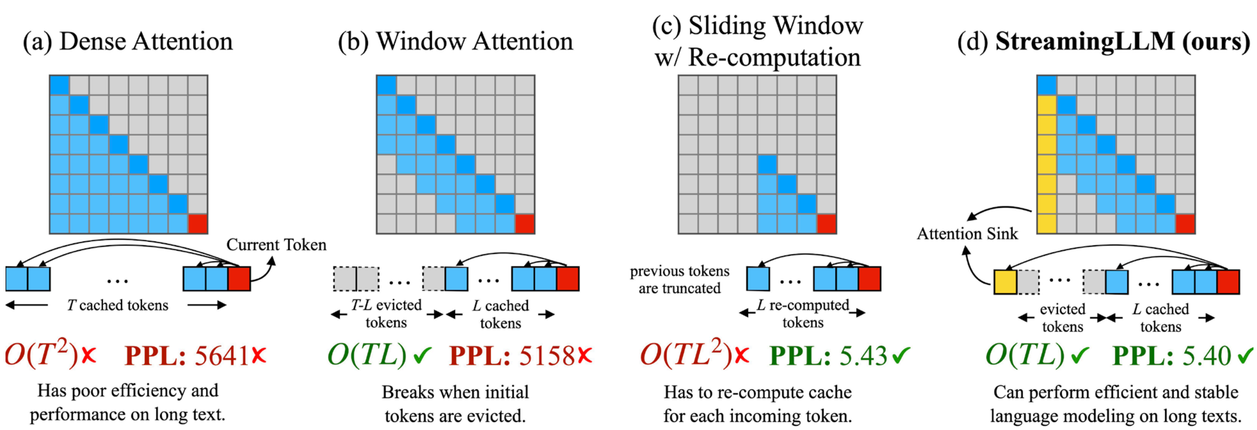


▲Figure 2: The same example with a validation set incorporated, resulting in a much smoother decision boundary and reduced overfitting.

Efficient Streaming Language Models with Attention Sinks

G. Xiao, Y. Tian, B. Chen, S. Han, M. Lewis
Sponsorship: MIT-IBM Watson AI Lab, Amazon, MIT Science Hub, NSF

Deploying large language models (LLMs) in streaming applications such as multi-round dialogue, where long interactions are expected, is urgently needed but poses two major challenges. Firstly, during the decoding stage, caching previous tokens' key and value states (KV) consumes extensive memory. Secondly, popular LLMs cannot generalize to longer texts than the training sequence length. Window attention, where only the most recent KVs are cached, is a natural approach, but we show that it fails when the text length surpasses the cache size. We observe an interesting phenomenon, namely an attention sink, that keeping the KV of initial tokens will largely recover the performance of window attention. In this paper, we first demonstrate that the emergence of an attention sink is due to the strong attention scores towards initial tokens as a "sink" even if they are not semantically important. Based on the above analysis, we introduce StreamingLLM, an efficient framework that enables LLMs trained with a finite length attention window to generalize to infinite sequence lengths without any fine-tuning. We show that StreamingLLM can enable Llama-2, MPT, Falcon, and Pythia to perform stable and efficient language modeling with up to 4 million tokens and more. In addition, we discover that adding a placeholder token as a dedicated attention sink during pre-training can further improve streaming deployment. In streaming settings, StreamingLLM outperforms the sliding window re-computation baseline by up to 22.2x speedup.



▲ Figure 1: StreamingLLM efficiently handles long texts by keeping initial tokens for stable attention computation, combined with recent tokens, offering consistent performance without excessive computational overhead compared to existing methods with limitations on text length or efficiency.

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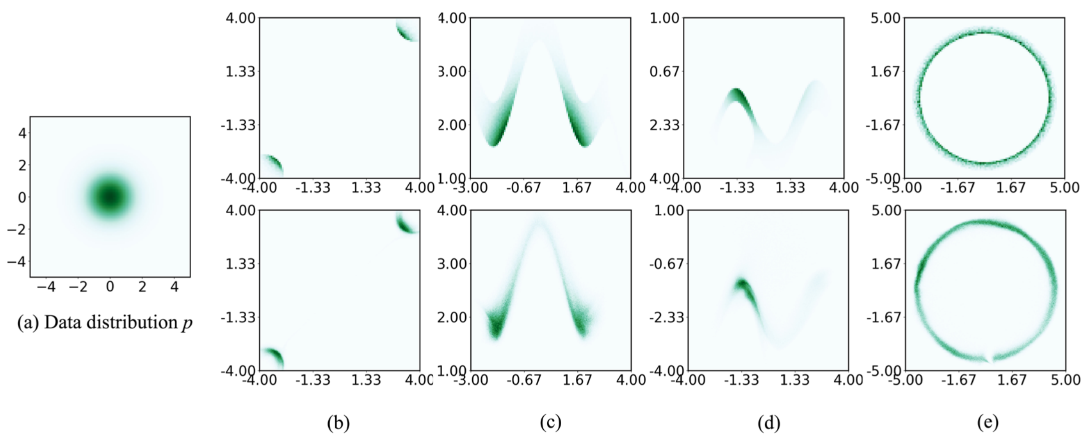
Rare Event Probability Learning by Normalizing Flows

Z. Gao, L. Daniel, D. S. Boning

A rare event is defined by a low probability of occurrence. In semiconductor manufacturing, accurate estimation of such small probabilities (e.g., the rare failure rate of a process, a device, or a circuit system) is of utmost importance. Conventional Monte Carlo methods are inefficient, demanding an exorbitant number of samples to achieve reliable estimates. Inspired by the exact sampling capabilities of normalizing flows, we propose normalizing flow assisted importance sampling, termed NOFIS. NOFIS first learns a sequence of proposal distributions associated with predefined nested subset events by minimizing KL divergence losses. Next, it estimates the rare event probability by utilizing importance sampling in conjunction with the last proposal. The efficacy of our NOFIS method is substantiated through qualitative visualizations, affirming the optimality of the learned proposal distribution, as well as a series of quantitative experiments, which highlight NOFIS's superiority over baseline approaches.



▲Figure 1: (a) The heatmap represents the data generating distribution. (b)-(e) The top row displays the theoretically optimal proposal distribution, while the bottom row illustrates the learned proposal distribution learned by our Algorithm.

On-the-Fly Learning for DNN Monocular Depth Estimation

S. Sudhakar, Z.-S. Fu, S. Karaman, V. Sze

Sponsorship: National Science Foundation, Real-Time Machine Learning program grant no. 1937501, the MIT-Accenture Fellowship, the Huang Phillips Fellowship, gift from Intel

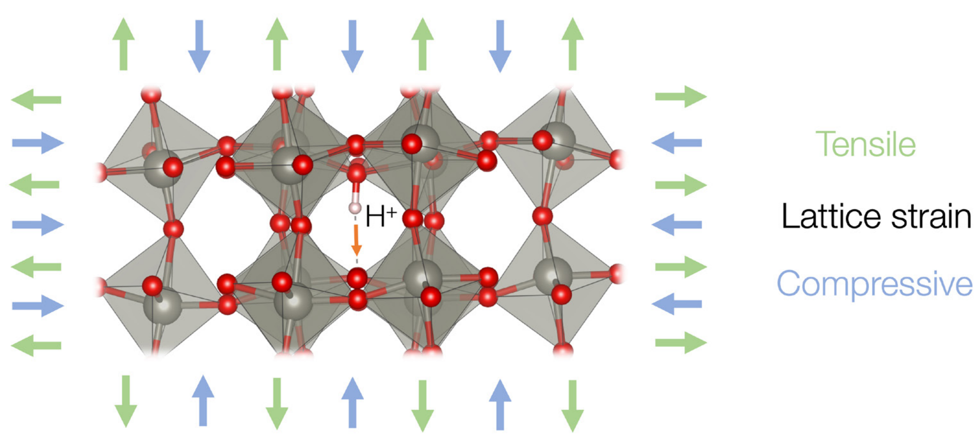
Monocular depth estimation with deep neural networks (DNNs) is critical for resource-constrained robots to avoid using power-hungry depth sensors. Since DNNs are known to perform poorly when the deployment environment is different from its training environment, we design a computation-efficient framework where the robot can adapt a monocular depth estimation DNN to a new environment on-the-fly. This form of training is compute and storage-limited, online (sequential video inputs), and self-supervised, making it challenging to accomplish with conventional training practices. As training on every image is computation-intensive, we propose using a novel acquisition function to select a subset of images for the DNN to train on. This function for training data selection is based on a unique combination of uncertainty, diversity, and self-supervised loss quality. With reducing the frequency of training to only 2.5% of the time instead of at every timestep as is conventionally done, leveraging our acquisition function achieves 5.6% higher accuracy on the explored dataset and 3.6% higher accuracy on the unexplored dataset compared to a fixed-periodic image selection strategy using the same number of training images. In addition, we require a buffer capacity of only 9 images, making it more suitable for storage-limited platforms compared to existing works that require two orders of magnitude more capacity. Finally, we deploy MC-dropout on the final layer of the DNN to efficiently estimate the uncertainty term in the acquisition function, which reduces the computational cost of the acquisition function by up to 9.1× compared to the traditional ensemble method.

Tungsten Bronzes forNeuromorphoc Computing: Can Lattice Strain Enhance Proton Migration in WO_3?

M. Siebenhofer, P. Zguns, B. Yildiz
Sponsorship: Max Kade Fellowship 2022 for M. Siebenhofer

Tungsten bronzes are insertion compounds with the general formula $MxWO_3$, where M (e.g. H, Li or Mg) is intercalated into WO_3. These compounds have a variety of applications, ranging from superconducting or electrochromic materials to catalysts and analog programmable resistors for artificial neural networks. For its application in neuromorphic computing, where the conductivity of WO_3 is modulated by ion intercalation, fast ion diffusion is key to obtain homogeneous ion distribution and fast switching between distinct resistive states. However, exact migration pathways in WO_3 are not well understood and novel strategies to enhance proton movement are desired.

In this contribution, we report the results of ab-initio investigations on proton migration processes in WO_3. We identify favourable binding sites for protons and migration pathways through the lattice. Using the nudged-elastic-band method, we investigate energetic barriers for proton hopping in WO_3 and evaluate their modulation in structures under tensile and compressive strain. If successful, targeted introduction of lattice strain (e.g. by doping) may be essential to improve both neuromorphic and electrochromic devices.



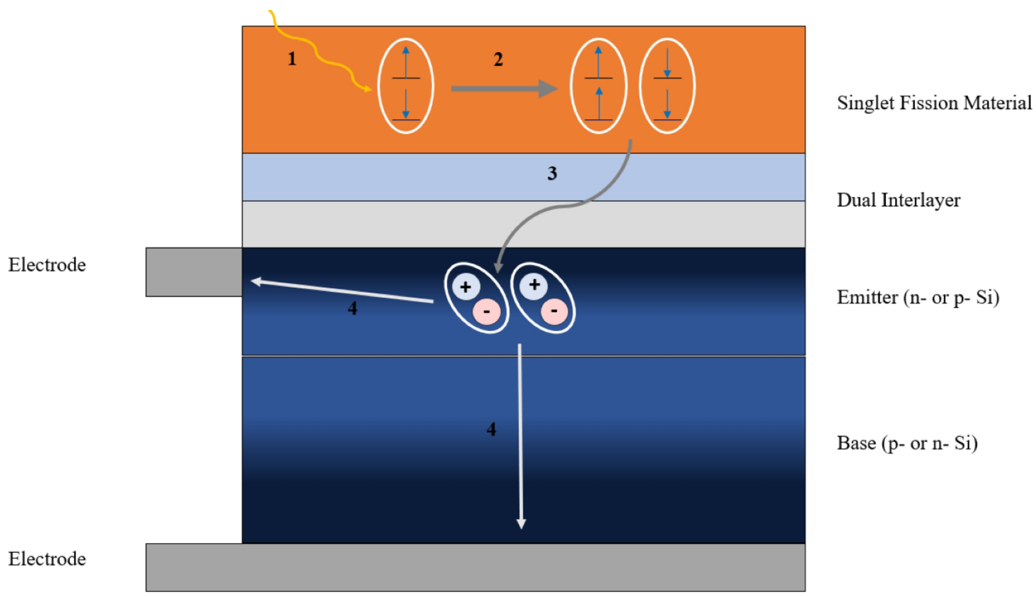
▲ Figure 1: Tensile and compressive lattice strain present a potential tool to modulate proton migration in WO_3.

Photonics and Optoelectronics

Silicon Solar Cell Quantum Yields Approaching 100% Due to Sensitization by Singlet Exciton Fission

N. N. Wong, C. F. Perkinson, K. Lee, A. Li, M. A. Baldo, M. G. Bawendi, W. A. Tisdale, K. Seo
Sponsorship: U.S. Department of Energy, Office of Basic Energy Sciences, and Samsung

Crystalline Silicon based solar cells currently dominate the global industry, but for single junction devices, the efficiencies are approaching the Shockley-Queisser limit. Sensitizing silicon to organic molecules that undergo the carrier multiplication process singlet exciton fission (SF), could provide a facile method to generate two electron-hole pairs per photon and improve efficiencies beyond the industry standard. Surface and bulk charge recombination and surface trap loss pathways have inhibited the transfer of energy from a SF material to silicon and decreased the overall performance. Herein, we employ a dual interlayer system to facilitate interfacial charge transfer states and surface passivation of trap states with a shallow junction device architecture for efficient carrier separation and extraction. We have demonstrated short circuit current from triplet excitons of tetracene and an enhancement to the external quantum efficiency of silicon solar cells.



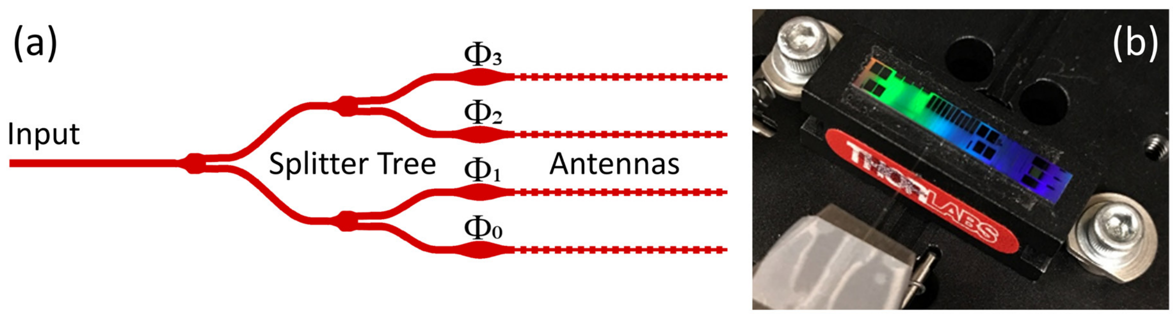
▲ Figure 1: Simplified schematic of a SF sensitized silicon solar cell device: (1) photoexcitation, (2) generation of two triplet excitons, (3) charge transfer into the surface of silicon, and (4) electron and hole separation to the electrodes.

Integrated Beam-Steering Optical Phased Arrays for Solid-State LiDAR Sensors

B. M. Mazur, D. M. DeSantis, M. R. Torres, M. Notaros, J. Notaros
Sponsorship: SRC JUMP 2.0 CogniSense, MIT Rolf G. Locher Endowed Fellowship, NSF Graduate Research Fellowship

Light detection and ranging (LiDAR) has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables 3D mapping with higher resolution than traditional RADAR. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability, increase production cost, and limit detection range. To address these limitations, solid-state optical-phased-array-based (OPA-based) LiDAR, which enables low-cost, high-speed, and compact non-mechanical beam steering, has emerged as a promising solution for next-generation LiDAR sensors.

In this poster, we discuss integrated beam-steering OPA architectures and devices for LiDAR sensors, highlighting their design spaces and tradeoffs. Additionally, we propose novel OPA subsystems for spatially-adaptive solid-state LiDAR sensors.



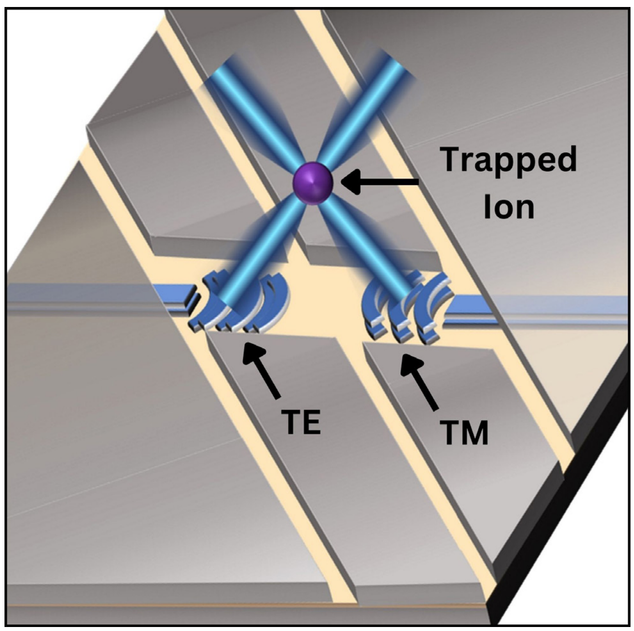
▲Figure 1: (a) Simplified schematic of an integrated optical phased array. (b) Photograph of a silicon-photonics chip with a large-scale integrated optical phased array.

Integrated Photonics for Advanced Cooling of Trapped-Ion Quantum Systems

S. Corsetti, A. Hattori, M. Notaros, T. Sneh, R. Swint, P. T. Callahan, F. Knollmann, E. R. Clements, D. Kharas, G. N. West, T. Mahony, C. D. Bruzewicz, C. Sorace-Agaskar, R. McConnell, J. Chiaverini, J. Notaros
Sponsorship: NSF Quantum Leap Challenge Institute Hybrid Quantum Architectures and Networks, NSF Quantum Leap Challenge Institute Quantum Systems through Entangled Science and Engineering, MIT Center for Quantum Engineering, NSF Graduate Research Fellowships Program, Department of Defense National Defense Science and Engineering Graduate Fellowship, MIT Cronin Fellowship, MIT Locher Fellowship

Trapped-ion systems are a promising modality for quantum information processing due to their long coherence times and strong ion-ion interactions, which enable high-fidelity two-qubit gates. However, most current implementations are comprised of complex free-space optical systems, whose large size and susceptibility to vibration and drift can limit fidelity and addressability of ion arrays, hindering scaling. Integrated-photonics-based solutions offer a potential avenue to address many of these challenges.

Motional state cooling is a key optical function in trapped-ion systems. However, to date, integrated-photonics-based demonstrations have been limited to Doppler and resolved-sideband cooling. In this work, we develop and demonstrate integrated-photonics-based systems and associated devices (conceptually depicted in Figure 1) for two advanced cooling schemes, polarization gradient and electromagnetically-induced transparency. This has the potential to improve cooling performance for trapped ions, enabling scalable quantum systems.



▲Figure 1: Conceptual diagram of integrated-photonics-based polarization-gradient-cooling system, demonstrating light of diverse polarizations simultaneously addressing ion positioned over ion-trap chip.

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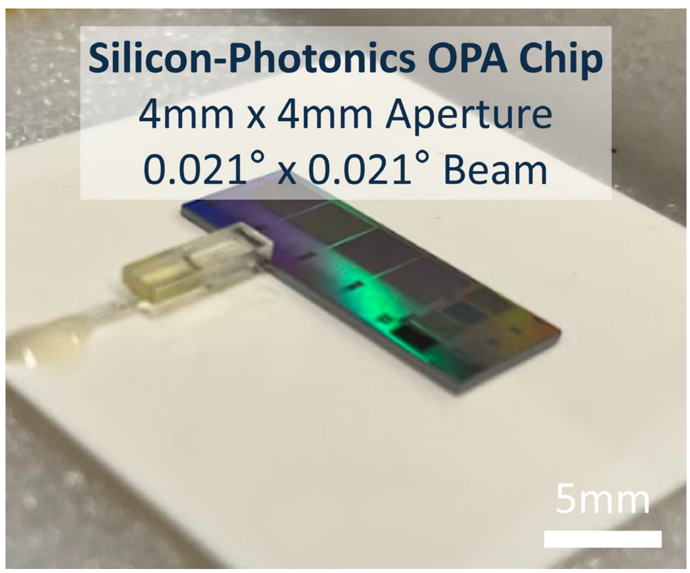
Spatially-adaptive Solid-state Optical-phased-array-based LiDAR

D. M. DeSantis, B. Mazur, M. R. Torres, M. Notaros, J. Notaros
Sponsors: SRC JUMP 2.0 CogniSense, MIT Rolf G. Locher Endowed Fellowship, and NSF Graduate Research Fellowship (Grant No. 1122374)

Light detection and ranging (LiDAR) has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables three-dimensional mapping with higher resolution than traditional radar. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability, increase production cost, and limit detection range. To address these limitations, solid-state optical-phased-array-based LiDAR (as shown in Figure 1), which enables low-cost, high-speed, and compact non-mechanical beam steering, has emerged as a promising solution for next-generation LiDAR sensors.

In this work, we propose and develop a novel spatially adaptive solid-state LiDAR system enabled by multiple-beam integrated-optical-phased-array subsystems and integrated optical-processing devices. This multi-beam adaptability enhances spatial awareness and reduces the back-end data processing traditionally associated with beam-rastering LiDAR by enabling the sensing and ranging of multiple targets simultaneously, without the need to scan the sensor's whole environment.



▲ Figure 1: Photograph depicting a large-scale optical-phased-array chip for solid-state beam forming and beam steering.

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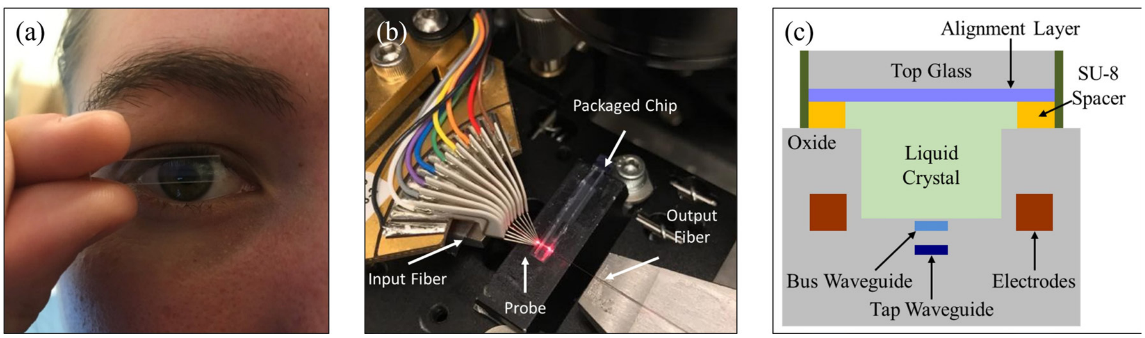
Integrated Visible-light Liquid-crystal-based Modulators for Augmented-reality Displays

A. Garcia Coleto, M. Notaros, T. Dyer, M. Raval, C. Baiocco, J. Notaros
Sponsorship: NSF CAREER Program (2239525), Defense Advanced Research Projects Agency (DARPA) Visible Integrated Photonics Enhanced Reality (VIPER) Program (FA8650-17-1-7713), MIT School of Engineering MathWorks Fellowship, NSF Graduate Research Fellowship (1122374)

Augmented-reality head-mounted displays (HMDs) that display information in the user's field of view have many wide-reaching applications in defense, medicine, gaming, etc. However, current commercial HMDs are bulky, heavy, and indiscreet. Moreover, current displays are incapable of producing holographic images with full depth cues; this lack of depth information results in eyestrain and headaches that limit long-term and wide-spread use of these displays.

To address these limitations, we are developing an integrated-photonics-based display that consists of a single transparent chip that sits directly in front of the user's eye and projects holograms that only the user can see. Specifically, we are developing integrated liquid-crystal-based phase and amplitude modulators that enable this integrated-photonics-based display architecture. This work paves the way towards a highly discreet and fully holographic solution for the next generation of augmented-reality displays.



▲Figure 1: (a) Photograph of a transparent integrated-photonics-based holographic display. (b) Simplified cross-sectional schematic of an integrated liquid-crystal-based modulator. (c) Photograph of an integrated photonic chip packaged with liquid crystal on an experimental setup.

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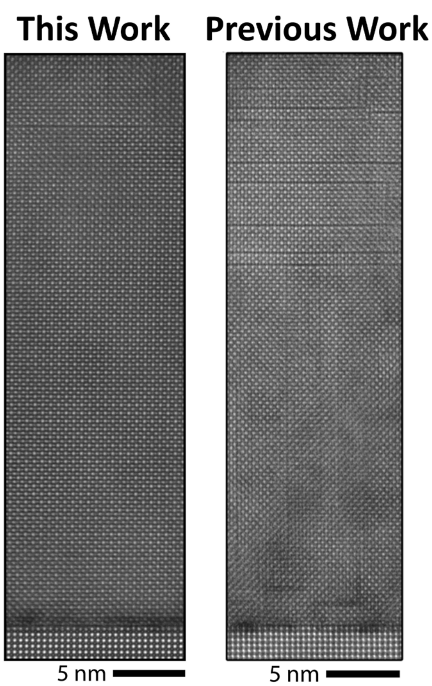
A Processing Route to Chalcogenide Perovskites Alloys with Tunable Band Gap via Anion Exchange

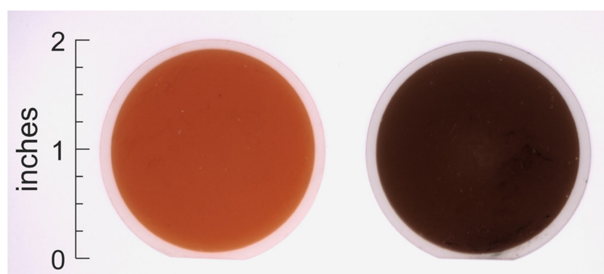
K. Ye, I. Sadeghi, M. Xu, J. Van Sambeek, T. Cai, J. Dong, R. Kothari, J. M. LeBeau, R. Jaramillo
Sponsorship: NSF (Grant Nos. 1751736, 1745302, 2224948)

Chalcogenide (sulfide and selenide) semiconductors in the perovskite crystal structure are anticipated to have favorable structural, optical, and electronic characteristics for solar energy conversion. The most studied compound is $BaZrS_3$, with a band gap of 1.9 eV. Alloying on the anion or cation sites has been explored to lower the band gap into a range suitable for single-junction solar cells. The pure selenide perovskite, $BaZrSe_3$, has been theoretically predicted to have band gap 0.5 eV lower than the sulfide. Experimental efforts from our group in 2023 demonstrated the alloying of $BaZrS_3$ with Se, and we confirmed that this alloy system features a tunable, direct band gap in the range of 1.4 – 1.9 eV.

Now we report an alternative processing route to synthesize these alloyed films. Our measurements on films suggest a reduced defect density and improved optoelectronic material properties compared to those of our previous efforts, as shown in Figure 1. We further showcase the utility of our processing at scale in Figure 2, via a demonstration on a polycrystalline film on a 2" Al_2O_3 wafer. More importantly, these results have strong relevance to the future manufacturing prospects of this material class. The gases and processing methodologies are similar to those for other well-known solar cell materials. The present work creates opportunities for research communities to inform the further development of chalcogenide perovskite technology.



▲Figure 1: Atomic-resolution electron microscopy image of a typical film cross section showing a noticeably reduced density of extended defects (left) compared to previous work (right). The images shown here correspond to films with the stoichiometry $BaZrS_{3-y}Se_y$ ($y \approx 2$).



▲Figure 2: Photographs of polycrystalline $BaZrS_3$ thin film samples grown on 2" Al_2O_3 wafers before (left) and after (right) selenization.

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Development of Ultra-Thin Perovskite Solar Module with Slot-die Printing

K. Yang, J. Mwaura, V. Bulović
Sponsorship: Tata Power Company Ltd., U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy

Owing to their solution-processibility, perovskite solar cells (PSCs) promise to offer a flexible, lightweight, and highly efficient alternative to crystalline silicon solar cells (c-Si). PSCs are able to open markets for solar deployment not accessible with c-Si while maintaining price-competitiveness with existing technologies. However, there are technological challenges to be addressed before PSCs are ready for large scale manufacturing.

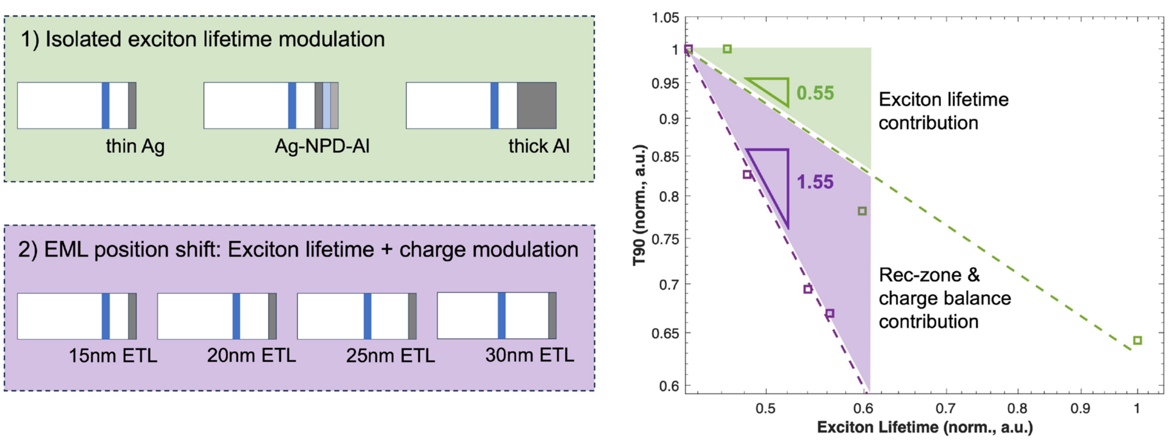
In contrast to the majority of research in PSCs which focuses on improving the stability and efficiency of small, spin-coated devices, this work aims to address challenges on the scaling and manufacturing front. Specifically, there exists a "scaling lag" which is seen when technologies are directly transferred from small devices to large area modules and manifests as decreased module efficiency and increased series resistance. In this work, slot-die coating is used to create large, 45cm^2 modules on 125um thick polyethylene terephthalate (PET) substrates with 7.5 cm^2 mini-modules exhibiting efficiencies of up to 7.4%. This process is the first working demonstration of a flexible, large-area PSC module fabricated with non-toxic solvents and establishes the baseline for the future transition to a 50μm peelable module which can be laminated onto transparent fabrics. To demonstrate the economic feasibility of commercial production, a techno-economic analysis is performed using Monte-Carlo simulation techniques to ensure price-competitiveness with current established solar technologies. Levelized Cost of Electricity values for flexible PSCs can be as low as 2.24¢/kWh compared to 3.16¢/kWh currently seen with mono-PERC silicon panels.

Successful demonstration of a flexible, large-area perovskite solar cell without toxic solvents will accelerate the industrialization of flexible photovoltaics. This would ultimately shift the solar landscape from mainly utility solar farms to a distributed model, further accelerating solar adoption.

Decoupling the Role of Exciton Lifetime, Charge Carrier Balance, and Dark Excitons in the Degradation of Blue OLEDs

J. Tiepelt, J. Song, C. Picart, A. Seeglitz, T.-A. Lin, S. Zhu, P. Satterthwaite, J. Li, M. A. Baldo
Sponsorship: U.S. Department of Energy – Office of Energy Efficiency & Renewable Energy

Organic light-emitting diodes (OLEDs) are the predominant technology for mobile display applications. The greatest remaining challenge is the stability of blue OLEDs, caused by long-lived triplet excitons. The effect of key parameters on OLED stability is not well understood to date. Here, we report a characterization technique that decouples an OLED's electronic properties from modulations of its emission layer's exciton lifetime by means of external plasmonic coupling. We show that the device's operational stability shows a much smaller than expected, square-root, dependence on exciton lifetime. As we only modulate emissive excitons here, it is possible that trapped 'dark' excitons dominate stability. In a second experiment, we vary the position of the emissive layer within the OLED, revealing a super-linear dependence of stability on the variation in charge balance and exciton lifetime. Last, we show strong indication of charge carrier imbalance resulting in trapped dark excitons dominating OLED stability.

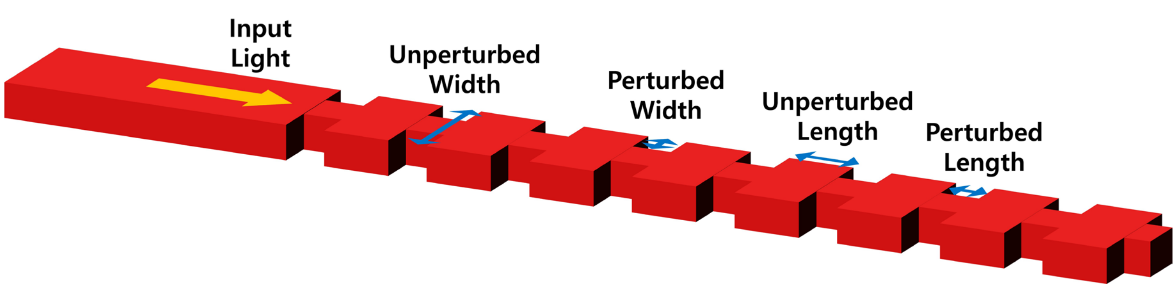


▲ Figure 1: Blue OLED stability in dependence of exciton lifetime variation vs. positional shift of the emitting layer. Device stability shown to be dominated by shifts in the recombination zone and charge carrier balance.

Integrated Optical Grating-Based Antennas for Solid-State LiDAR Sensors

M. R. Torres, S. Corsetti, D. M. DeSantis, A. G. Coleto, B. Mazur, M. Notaros, J. Notaros
Sponsorship: SRC JUMP 2.0 CogniSense

Light detection and ranging (LiDAR) has emerged as a vital and widely-used sensing technology for autonomous systems, such as autonomous vehicles, since it enables 3D mapping with higher resolution than traditional RADAR. However, current commercial LiDAR systems utilize mechanical beam-steering mechanisms that decrease reliability, increase production cost, and limit detection range. To address these limitations, solid-state optical-phased-array-based (OPA-based) LiDAR, which enables low-cost, high-speed, and compact non-mechanical beam steering, has emerged as a promising solution for next-generation LiDAR sensors. In this poster, we develop integrated optical grating-based antennas, a critical device responsible for light emission in these solid-state LiDAR systems. We develop a device synthesis algorithm, design a suite of antennas with varying operating modalities, and discuss their design tradeoffs when applied to OPA subsystems.



▲ Figure 1: Simplified schematic of an integrated optical grating-based antenna with key design parameters labeled.

Determining Charge Carrier Transport Parameters from Microscopy Data

T. J. Sheehan, W. A. Tisdale
Sponsorship: Massachusetts Institute of Technology, Department of Chemical Engineering

Time-resolved microscopy techniques are increasingly used to image the transport of excited charge carriers and excitons in materials. Typically, transport parameters such as diffusivity are extracted by generating a spatially localized population of excited charge carriers, then measuring the growth of the spatial charge carrier profile over time. However, current analysis techniques are highly sensitive to the shape of the initial charge carrier profile, and can result in large errors for even small deviations from an assumed profile shape. Additionally, these measurements may be significantly impacted by shot noise at common experimental conditions. Here, we apply conventional analysis techniques to simulated one-dimensional transport measurements to quantify the effects of non-ideal carrier spatial profiles and shot noise on the diffusivities extracted from microscopy data. We show that non-ideal profile shapes can lead to errors almost as large as 50%. Using these results as a baseline, we then propose an alternate analysis technique that uses convolutions of Gaussian functions with the measured charge carrier spatial profiles to both smooth the effects of shot noise and to measure the growth of the spatial profiles. We demonstrate that this algorithm outperforms traditional analysis techniques at recovering diffusivities from simulated data sets, displaying a slightly reduced sensitivity to shot noise and a significantly lower sensitivity to the shape of the initial charge carrier spatial profile. Finally, we apply this technique to experimental data to illustrate different strategies for extending this algorithm to accurately extract parameters for diffusion that occurs in two or more dimensions.

Understanding Ultrafast Energy Transfer in Mixed-Dimensional Perovskite Heterostructures

M. Chattoraj, W. A. Tisdale
Sponsorship: U.S. Department of Energy, Office of Science, Basic Energy Sciences, award no. DE SC0019345.

Lead halide perovskite nanomaterials are an intriguing class of semiconductors due to their many remarkable optical properties, including long-lived charge carriers and spectrally narrow emission that is synthetically tunable across the visible light spectrum. Perovskites are of interest for many optoelectronic applications ranging from photovoltaics to displays. To increase the efficiency of optoelectronic devices incorporating nanomaterials, a detailed understanding of energy transfer in nanoscale systems is necessary.

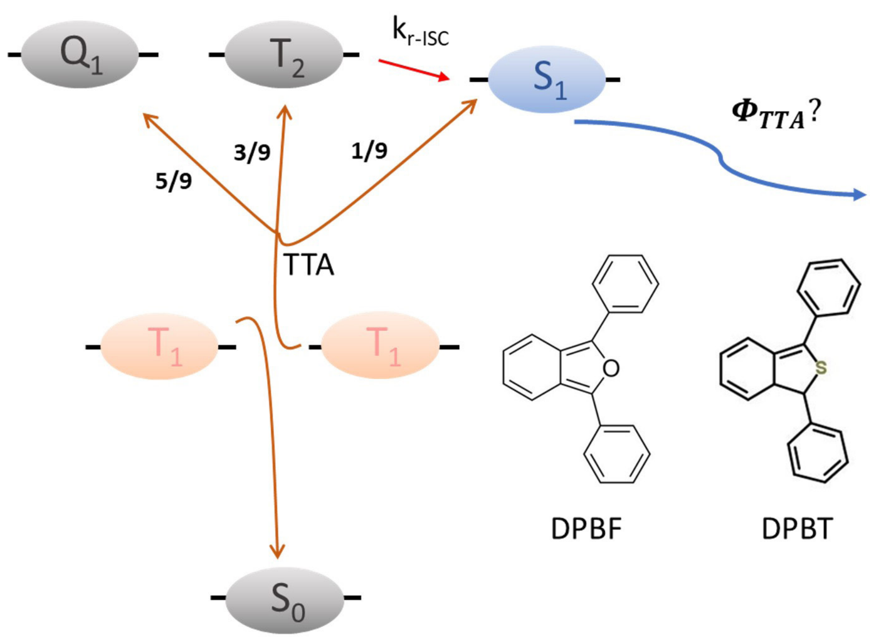
Although exciton transfer in colloidal semiconductors has traditionally been described by Förster resonance energy transfer (FRET), this framework does not fully capture exciton behavior in many novel materials. Lead halide perovskites have been shown to exhibit energy transfer rates far exceeding Förster theory predictions, thus posing an intriguing material platform for establishing a more detailed understanding of exciton dynamics. As devices increasingly incorporate nanomaterials such as quantum dots, understanding energy transfer between materials of varying dimensionality becomes crucial. Rigorous characterization of energy transfer mechanisms in perovskite-based heterostructures requires synthesis of high-quality perovskites. Here, perovskites of various dimensionalities are synthesized and combined into heterostructures. In the future, energy transfer in these heterostructures will be studied using time-resolved photoluminescence (TRPL) and ultrafast transient absorption (TA) spectroscopy. Ultimately, we aim to build a thorough, quantitative understanding of energy transfer mechanisms in novel nanomaterials, which will contribute to the development of highly efficient optoelectronic devices including photodetectors, displays, and solar cells.

High Level Intersystem Crossing in Triplet-triplet Annihilation Photon Upconversion Materials Diphenylisobenzofuran and Diphenylisobenzothiophene

O. Nix, T.A. Lin, C.A. Kim, C. Perkinson, M. A. Baldo
Sponsorship: U.S. Department of Energy Office of Basic Energy Sciences (DE-FG02-07ER46474)

Triplet-triplet annihilation (TTA) presents a promising photon upconverion (PUC) platform that can improve the efficiency and stability of blue organic light emitting devices. TTA is a spin-dependent process that converts two low energy triplet states to a bright singlet state. However, the TTA process can also form dark high energy triplet states that lead to reductions in efficiency and device stability. There is a fundamental limit on the fraction of singlet states that can be produced through TTA, limiting its PUC efficiency.

In this work, tuning reverse intersystem crossing (r-ISC) from dark triplet states to bright singlet states was probed as a strategy for surpassing this limit. TTA materials diphenylisobenzofuran and diphenylisobenzothiophene were modelled to predict their relative r-ISC rates, and were characterized in solutions and spun cast films. Fast r-ISC was inversely correlated with TTA efficiency, suggesting low level r-ISC is a significant loss pathway to TTA.

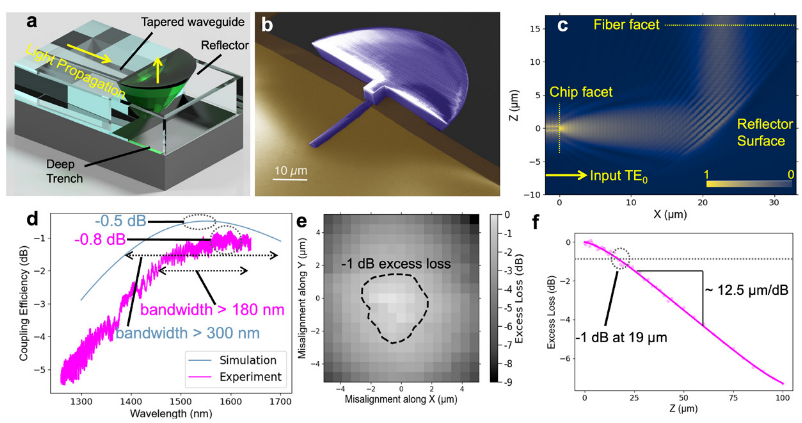


▲ Figure 1: Schematic of the triplet-triplet annihilation (TTA) process, where two triplet excitons annihilate to form either a bright singlet or dark triplet or quintet state. Increased formation of the bright singlet through r-ISC is investigated in DPBF and DPBT as a strategy for increasing Φ_{TTA}.

High-performance Facet-attached 3D Micro-reflectors for Scalable Fiber-to-Chip Coupling

L. Ranno, J. X. B. Sia, C. Popescu, D. Weninger, S. Serna, S. Yu, L. C. Kimerling, A. Agarwal, T. Gu, J. Hu
Sponsorship: NSF Convergence Accelerator (Award Number: DE-AR0000847)

Leveraging the mature fabrication processes developed by the electronics industry, silicon photonics is poised to revolutionize a variety of application spheres, including telecommunications, environmental sensing, and quantum and classical computing. Still, the lack of a scalable and cost-effective packaging solution to interface optically to photonic integrated circuits is proving to be a barrier preventing the wide adoption of photonics. Convergence on a unified optical coupling scheme that meets all the industry requirements is imperative for the success of the field. Among the proposed approaches to address this optical "packaging bottleneck," micro-optics fabricated via two-photon polymerization (TPP) have achieved promising performance metrics. Nevertheless, the research community has primarily focused on uncladded waveguides, which are not the industry standard and require customized cladding removal steps, limiting the scalability of these solutions. We present results on a new scalable coupling scheme that takes advantage of the design freedom enabled by TPP by fabricating 3D printed micro-reflectors directly on wave-guide facets. The shape of the micro-reflector is optimized to both redirect and reshape the beam exiting the waveguide, hence maximizing coupling with a standard flat-cleaved SMF-28 optical fiber positioned vertically above the chip. The deep trenches where the reflectors reside are fabricated during the edge coupling formation step, which is already part of the fabrication flow in photonic foundries. The reflectors can be seamlessly printed onto the waveguide facets at the backend after receiving the fabricated photonic chips. Simulations and experimental results demonstrate the excellent performance of the reflectors, which boast experimentally verified insertion losses of only -0.8 dB, with bandwidths over 180 nm. Additionally, the 1-dB in-plane and out-of-plane alignment tolerances of the devices reach approximately 2 µm and 19 µm, respectively, making the reflectors compatible with high-throughput passive alignment coupling approaches.



▲ Figure 1: (a) Schematic and (b) False-colored scanning electron microscope image of the reflector. (c) Electric field propagating through the system. (d) Waveguide-to-fiber coupling efficiency against wavelength. (e) In-plane and (f) out-of-plane fiber alignment tolerances.

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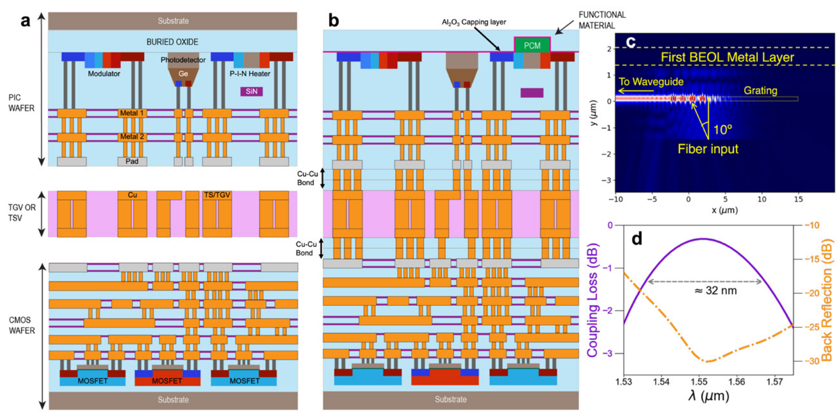
SuMMIT: A New Platform for Photonic Heterogeneous Integration

L. Ranno, K. P. Dao, J. X. B. Sia, J. Hu
Sponsorship: NSF (Award Number: 2328839)

The exponential growth that silicon photonics has experienced can be primarily attributed to the infrastructure developed by the electronics industry. Leveraging the complementary metal-oxide-semiconductor (CMOS) fabrication processes, photonics foundries have quickly upscaled manufacturing and now commonly offer waveguides with propagation losses on the order of 1~3 dB/cm, modulators with bandwidths of ~40 GHz, and high-efficiency integrated germanium photodetectors. Even though the current toolkit available from foundries is certainly impressive and enables the entire photonics infrastructure of today, a significant number of functionalities, including on-chip light emission and gain, isolation, memory, and electro-optic modulation, is missing as a result of material incompatibilities with the CMOS process. To include these exotic materials in photonic circuits while maintaining good interaction with the waveguide layer, the research community has been forced to either dig trenches in the back end of the line (BEOL) layers of foundry wafers or fabricate custom chips, both of which have significant disadvantages limiting the scalability and technological relevance of such implementations.

We propose a new heterogeneous integration approach that is fully foundry compatible, namely SuMMIT–Substrate Inverted Multi-Material Integration Technology. In SuMMIT, the photonic wafer is bonded to a through-glass or through-silicon via wafer, which acts as a handle wafer and an electrical interface to the photonic wafer. The through-glass via wafer may be bonded to a PCB or CMOS wafer. After bonding, the back of the photonic wafer is removed through a combination of etching and chemical-mechanical polishing, exposing the waveguide layer. At this point, materials can be deposited or bonded as needed. Additionally, the creation of a second interface (back) decouples the electrical and optical input/output and enables new designs that could not be realized before. For instance, the BEOL metal layers can be used to produce highly efficient grating couplers or antennas.



▲ Figure 1: Illustration of the SuMMIT technology stack (a) before bonding and (b) after bonding, back-removal, and material deposition. (c) Electric field of a grating coupler with BEOL metal as a reflector. (d) Performance of the grating implemented in (c).

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Crown Ether Decorated Lead Silicon Photonic Sensors for Pb^{2+} Environmental Detection

L. Ranno, Z. Xu, J. Hu, J. Xu, B. Sia

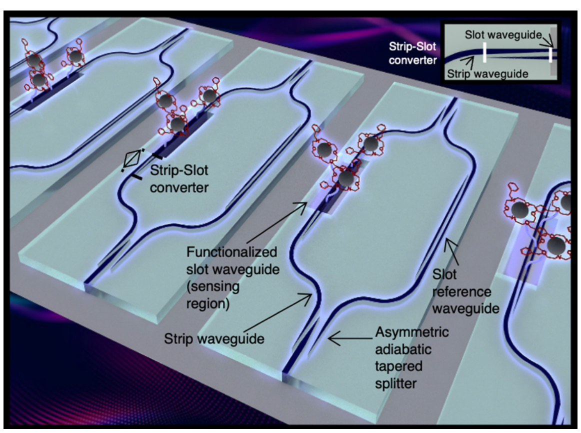
Lead (Pb^{2+}) poisoning is a pressing global public health crisis. Pb^{2+} toxification leads to various adverse effects on health, e.g neurological damage or increased infant mortality. Unfortunately, public policies to address this issue have been lackluster.

Here we present the crown ether decorated silicon photonic platform for lead ion detections. Crown ethers are cyclic polyethers with the remarkable ability to selectively bind to specific ions based on their physical and chemical properties. The proposed sensor operates through the means of optical interference. More specifically, ions binding to the crown ether functionalization layer lead to a change in local refractive index, or equivalently a wavelength shift of the interferometer resonance.

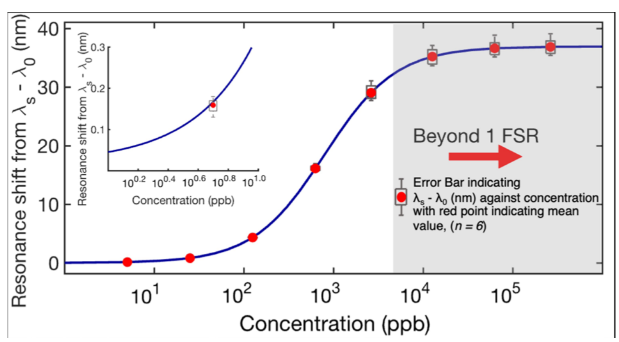
Figure 1 illustrates the integrated Pb^{2+} sensor based on a Mach-Zehnder interferometer. The crown ethers are functionalized on one of the waveguide arms with the other used as reference. During operation, the sensor is first exposed to deionized water to collect a reference spectrum, followed by exposure to the analyte solution and finally flushing with water and measurement of a second optical spectrum. Larger wave-length shifts between the two spectra indicate higher Pb^{2+} concentrations, as shown in Figure 2.

We tested the validity of the calibration curve across different environmentally related samples and verified them with Inductive coupled plasma mass spectrometry prior to the experiment. Performance in environmental performance showed excellent sensitivity and selectivity, indicating the resilience of the proposed solution.

This work innovates on three aspects. First, we demonstrate that applying the Fischer esterification protocol successfully couples carboxylic acid groups with hydroxyl groups on pretreated SiO_2 waveguide surfaces. Second, the developed sensor enables swift analyte testing with high detection accuracies, matching the state-of-the-art at a significantly lower price point and greater portability. Third, this integrated platform can leverage high-precision and cost-effective manufacturing techniques for scaling up production.



▲ Figure 1: 3-D illustration of photonic Pb^2+ ion sensor based on crown ether decorated silicon platform. Functionalization performed in sensing region is indicated.



▲ Figure 2: Calibration curve of sensor when exposed to reference Pb^2+ concentrations of 0, 5, 25, 125, 625, 2625, 12625, 62625, and 262625 ppb via cumulative testing approach.

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Plasmonic Nanoparticle Lattices as Optical Cavities for Thin Film Colloidal QD Lasers

S. Srinivasan, J. Guan, R. Zhang, K. McFarlane-Connelley, M. G. Bawendi, V. Bulović
Sponsorship: Samsung Semiconductor Co., U.S. Department of Energy

Thin film nanoscale lasers have applications ranging from on-chip optical interconnects, virtual and augmented reality displays, and optical wireless communication. To realize these applications, both nanoscale optical cavities and high quantum yield emitters are required. Quantum dots (QDs) are semiconductor nanoparticles with discrete energy levels generated through quantum confinement with size and composition tunable emission. Current thin film lasers utilize molecular beam epitaxy to grow optical cavities and QDs, requiring fabrication with expensive high vacuum systems. To reduce manufacturing costs, both a simple optical cavity and a solution processable gain medium are required. Colloidal QDs are synthesized in solution and are chemically stabilized with organic capping ligands. They have demonstrated synthetically tunable emission and near unity quantum yield. Plasmonic nanoparticle lattices are nanometer spaced arrays of metal nanoparticles that couple local surface plasmon resonance modes of individual nanoparticles with diffraction modes generated by the array. They are fabricated in a single liftoff process, reducing manufacturing complexity. The lattice resonance mode is also easily tunable through control of the lattice geometry, spacing, and surrounding refractive index.

The combination of plasmonic nanoparticle lattices and colloidal quantum dots creates a new paradigm for the fabrication of nanoscale lasers with tunable emission and low pumping thresholds. In this work we demonstrate an optically pumped laser with perovskite colloidal quantum dots integrated into Al-nanoparticle lattices. The lattices were fabricated with a single step electron beam lithography and liftoff process. By varying lattice periodicity, lasing emission directionality was controllable by up to 12 degrees off-normal.

Optimized design of Vapor Transport Co-Deposited Perovskite Photovoltaics

T. Kadosh Zhitomirsky, S. Srinivasan, W.-J. Hsu, E. Pettit, R. J. Holmes, H. L. Tuller, V. Bulović
Sponsorship: U.S. Department of Energy

Metal-halide perovskites have demonstrated high photo-electrical conversion efficiencies, superior to other thin film semiconductors, hence viewed as promising candidates to replace silicone as solar cell materials. However, popular solution-based processing routes impose a challenge when coming to up-scale. Vapor Transport Deposition (VTD) is a readily scalable and low-cost alternative method for perovskites production. Being solvent-free, they bypass solvent related challenges, namely uniform coverage of large areas, chemical compatibility, and toxicity. As a low-cost alternative to thermal evaporation, VTD has the potential to deposit organic and inorganic perovskite precursor materials either sequentially or via co-deposition. Furthermore, VTD potentially offers higher tunability of deposition parameters, to enable film growth with improved composition and microstructure control. Yet, being a newly developing technique, we still need to prove its viability in producing high-quality perovskite films.

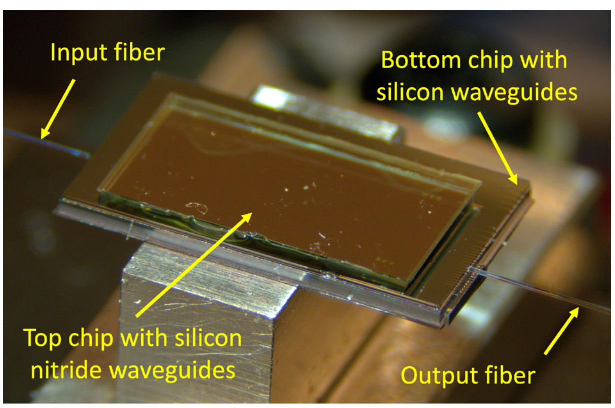
We are currently working with a custom-made VTD system, focused on optimization of co-deposition of lead iodide and methylammonium iodide with the aid of carrier gases. Additionally, we address the design of the device. We conclude that for pristine MAPI, small lead iodide excess leads to higher power conversion efficiencies. We found the n-i-p structure as preferable over the p-i-n one. We also learned the importance of choosing appropriate electrodes and transport layers, as well as applying post-deposition treatments. These findings can serve us in fabricating solar cells utilizing this new technique.

Inter-chip Optical Couplers for Automated Photonic Integrated Circuit Packaging

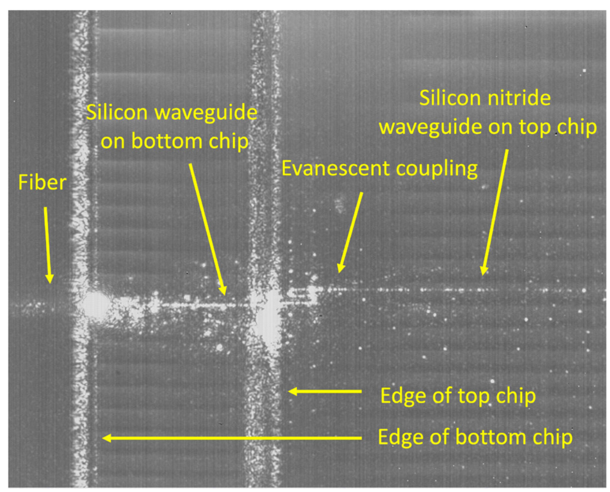
D. M. Weninger, S. Serna, L. Ranno, L. C. Kimerling, A. M. Agarwal
Sponsor: NSF

The use of silicon photonic integrated circuits (Si-PICs) and optical fibers in telecommunications networks offers significant system improvements in terms of latency, energy consumption, and data capacity compared to electrical integrated circuits and copper wiring. However, the manual alignment and bonding of bulky optical fiber arrays to the edge or top of Si-PICs with sub-micron precision create a significant challenge to their widescale adoption. The development of integrated couplers connecting Si-PICs to optical printed circuit boards without using flyover fiber arrays offers an opportunity to advance photonics packaging, as ball grid arrays advanced microelectronics away from wirebonding. Specifically, these couplers can enable automated assembly of Si-PICs using pick-and-place tools readily available through the microelectronics infrastructure.

To this end, studies are investigating several methods for inter-chip coupling such as 3D printed microlenses and mirrors, etched surface gratings, and cantilevers. This work investigates evanescent coupling, a method offering low coupling losses at the expense of alignment tolerances on the order of several hundred nanometers. We fabricated, packaged, and tested prototypes using a novel evanescent coupler design to determine manufacturing feasibility. The resultant prototype was the first demonstration of an inter-chip evanescent coupler between silicon and silicon nitride wave-guides. The measured coupling efficiency for telecommunications wavelengths was approximately 93%--the lowest reported for a silicon-based inter-chip evanescent coupler. Likewise, the measured alignment tolerance was roughly 2.48 micron–an order of magnitude larger than typical evanescent coupling tolerances and large enough to enable automated flip-chip assembly. In addition, the coupler's footprint was roughly a third of the typical length and a tenth of the typical width, versus comparable designs. Developing a high-performance inter-chip coupler using standard complementary metal-oxide semiconductor foundry materials can eliminate the packaging inefficiencies of fiber-to-chip connections to enable mass manufacturing of Si-PICs.



▲ Figure 1: Inter-chip evanescent coupling prototype. Light travels through input fiber to bottom chip using edge coupler, couples to top chip using evanescent coupler, couples back down using second evanescent coupler, and is collected at output fiber.



▲ Figure 2: Image taken by infrared camera mounted directly above prototype, looking through back of glass top chip. Injected light at 1.55-micron wavelength can be seen coupling from fiber and to top chip using evanescent coupler.

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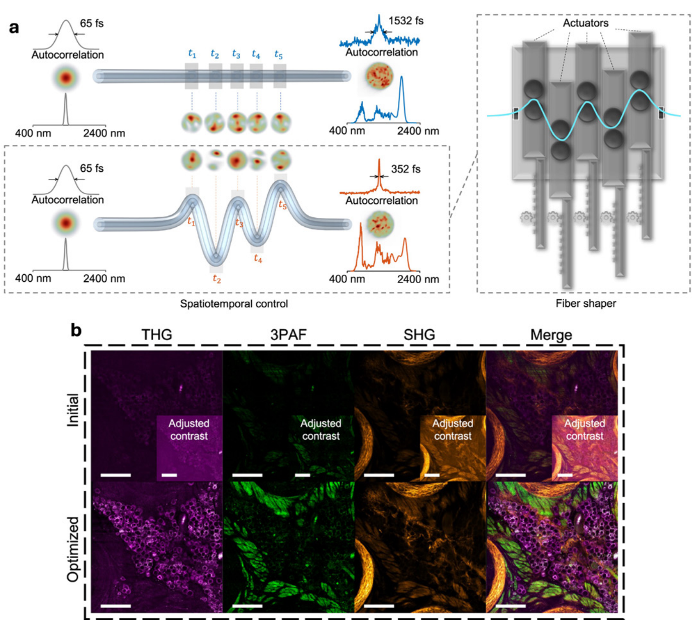
Tunable Broadband Fiber Source for Multiplexed Nonlinear Microscopy

L. Yu, H. Cao, K. Liu, T. Qiu, S. You
Sponsorship: MIT Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics startup funds, Jameel Clinic, Chan Zuckerberg Initiative, Radon Institute, Koch Institute, Research Corporation for Science Advancement

Nonlinear microscopy is a powerful imaging technology for living, intact biological tissues with the capability of revealing morphological and chemical contrasts at a molecular level in a dynamic environment. Many intrinsic molecules and structures interact with optical fields via various nonlinear processes, including second/third harmonic generation, two-/three-photon autofluorescence, and coherent Raman scattering, offering specificity to endogenous contrasts by which the unperturbed biological activities are discernible. While nonlinear microscopy promises a multiplexed detection scheme for rich biological information, an unsolved challenge remains since the excitation source must cover wavelengths from visible to short-wave infrared with high power density to optimize the sensitivity for each contrast, due to the small nonlinear cross-sections.

To address the unmet need for multiplexed nonlinear microscopy, we demonstrate multimode fiber (MMF) as a compact and cost-effective solution as opposed to the existing techniques such as multi-head lasers and optical parametric oscillators/amplifiers. MMF is an efficient wavelength conversion platform, populating a narrowband pump source to a broadband, high-peak-power, supercontinuum source. While the intermodal coupling and dispersion have long been conceived as detrimental to the pulse duration and beam quality, we demonstrate the spectral, temporal, and spatial properties of the pulses can be tailored toward a better imaging quality by carefully seeding and engineering the pulse propagation. In particular, we developed a device – a fiber shaper–that deforms the MMF via a sequence of motor steppers to introduce programmable disorder to modify the pulse propagation (Figure 1). In addition, we optimized the launching condition by shaping the pump beam for dispersion engineering using a spatial light modulator. By leveraging the programmable disorder and wavefront shaping, we can enhance the spectral density, reduce the pulse duration, or improve the beam quality for diverse imaging modalities in nonlinear microscopy (Figure 2). This study has led to a broadband, high-peak-power, and tunable light source that promises high-content, multiplexed, in vivo imaging technology for a wide array of biological applications.



◀Figure 1: (a) Spectral-temporal-spatial customization in MMFs by introducing programmable disorders via fiber shaper. (b) Label-free imaging of mouse whisker pad tissue at 1225 nm excitation using fi-ber source with initial and optimized set-tings. Scale bars: 200 μm.

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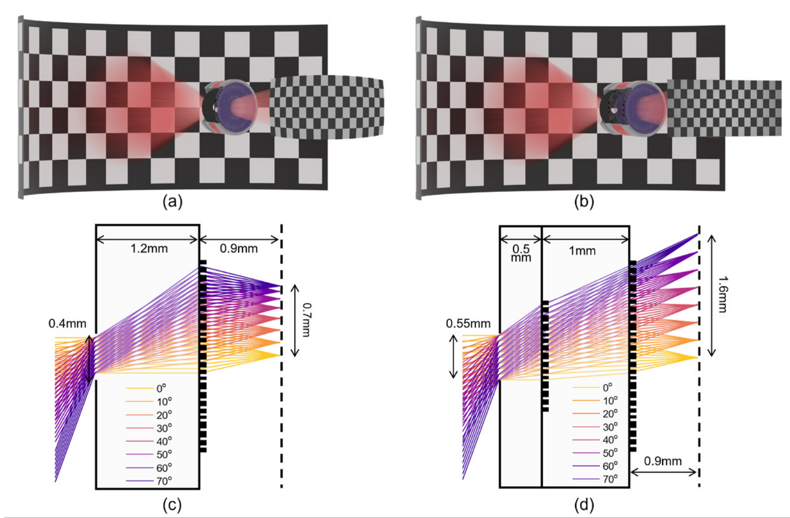
Compound Metalens Enabling Distortion-free Imaging

H. Zheng, F. Yang, H. Lin, M. Y. Shalaginov, Z. Li, P. Burns, T. Gu, J. Hu
Sponsorship: Defense Advanced Research Projects Agency

Optical metasurfaces comprising sub-wavelength scale meta-atoms provide a versatile platform for wavefront control with a compact form factor. Major advances over the past decade in their design, manufacturing, and integration have catalyzed imminent commercial deployment of functional metasurface components in numerous beachhead markets such as structured light, computer vision, near-eye displays, and beam steering. Optical distortion, deviation from rectilinear projection that deforms images, is an important design specification for these applications involving imaging or image/pattern projection. However, while other image-forming attributes of meta-optics including various other forms of aberrations (spherical, astigmatism, coma, and chromatic aberrations) have been extensively studied, distortion and its compensation remain underexplored.

We propose a generic recipe for designing metalenses with on-demand distortion characteristics, which can customize (or arbitrarily define) the relation between the ray angle of incidence and the corresponding image height for radially symmetric optics. Unlike a single-layer metalens whose distortion is fixed, constrained by its aberration minimization condition, the extra degrees of freedom afforded by a doublet metalens enable concurrent elimination of monochromatic aberrations and specification of custom-tailored distortion. We experimentally validated our design approach through demonstrating a doublet metalens at 940-nm wavelength that simultaneously achieves 140° field-of-view, diffraction-limited performance, and less than 2% distortion (Figure 1). In comparison, a singlet metalens without distortion engineering suffers from distortion as large as 22%.



▲Figure 1: Comparison of imaging distortion in singlet and compound metalenses. (a) A singlet metalens suffers from large barrel distortion. (b) Compound metalens effectively eliminates the barrel distortion. Ray-tracing modeling of the (c) singlet and (d) compound metalenses, respectively. The light incident angles (in air) vary between 0° and 70° with a step of 10°.

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Power Devices and Circuits

Large-Signal Characterization of Piezoelectric Resonators for Power Conversion

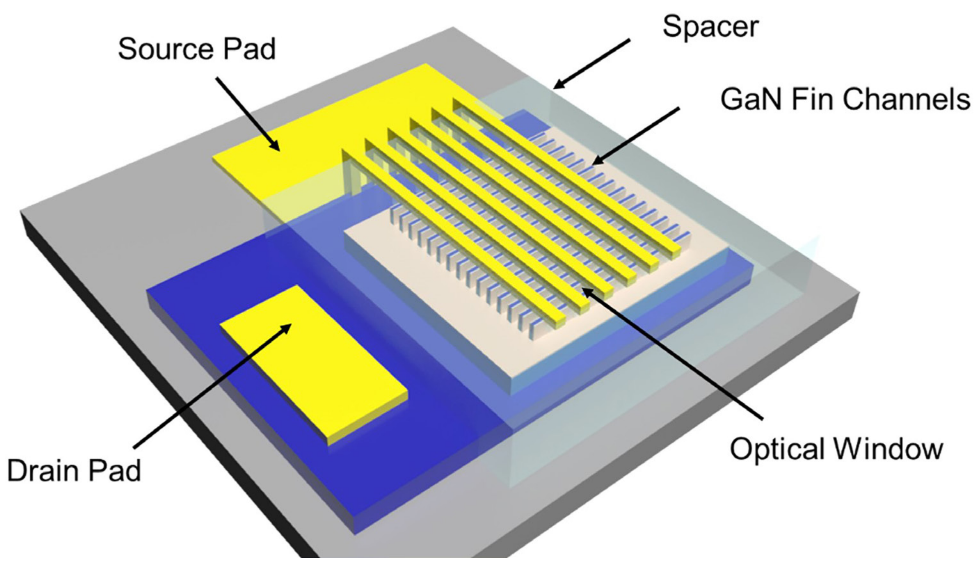
A. K. Jackson, J. W. Perreault, J. H. Lang, D. J. Perreault
Sponsorship: Texas Instruments, NSF Graduate Research Fellowship

As the world moves towards increased electrification and integration of renewable energy sources, there is a need for smaller, lighter, and more efficient power converters. Magnetics are key components of conventional power converters, but they are often the bottleneck to achieving high power density due to their size, weight, and poor performance at small sizes. Piezoelectric devices, when operated in their inductive regime, can serve a purpose similar to that of magnetic components and offer favorable scaling properties as components are miniaturized. Several sources have demonstrated the viability of piezoelectric-based power converters, but selection of the optimal material and component size is limited by a lack of data on the performance of these materials at high drive levels. This work aims to fill that gap by collecting data to examine the variation in resonator quality factor, a geometry-independent metric for the power processing efficiency. The quality factor is measured across a range of drive levels for multiple resonator sizes, frequencies, and materials. By normalizing the collected data against resonator geometry, material trends are derived that can predict resonator losses under high drive levels, offering more insight into realistic converter operation than the currently available small-signal data sheet values. Based on these trends, implications for converter efficiency and selection of material and dimensions are discussed.

First Demonstration of Optically Controlled Vertical GaN Power FinFETs

J.-H. Hsia, J. Perozek, T. Palacios
Sponsorship: Office of Naval Research (Grant No. N00014-22-1-2468)

In recent years, the boost in consumer electronics and data centers has increased the electricity demand. The delivery and transformation of power though electric grids require many efficient power converters and electronics that can withstand high current and voltages. However, traditional power electronics are mostly electrically triggered, which can complicate the circuitry design and cause electromagnetic interference (EMI). The use of optically triggered devices will simplify the circuitry design, reduce EMI, and potentially increase the operating frequency, which can lead to more reliable systems with reduced costs. However, most optically triggered devices require the use of complex and expensive ultraviolet lasers due to low optical responsivities. In this work, we have demonstrated optically controlled vertical GaN transistors with J_{DS} > $90A/cm^2$ at V_{DS} = 3V under an illumination intensity of 1μW, which translates into a high optical responsivity, > 10^5 A/W, allowing such devices to be triggered by light-emitting diodes. The initial results have demonstrated potential of these devices for future high-power electronics.



▲ Figure 1: Three-dimensional schematic of an optically triggered, vertical GaN fin field-effect transistor (FinFET).

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In-situ Monitoring of GaN Power Transistor Parameters Under Continuous Hard-switching Operation

A. Massuda, J. A. del Alamo
Sponsorship: Analog Devices

Gallium Nitride (GaN) transistors have garnered attention in the field of power electronics due to their high-speed switching capabilities, low on-resistance, and excellent thermal properties. GaN devices are commonly used in applications like power supplies, electric vehicles, and Radio Frequency (RF) amplifiers. However, their switching reliability is a crucial consideration.

There are many challenges to be addressed to improve GaN switching reliability, including robust gate drive circuitry, effective thermal management, and protection against voltage and current spikes during switching events. Additionally, GaN transistors can be sensitive to voltage and temperature stresses, requiring careful consideration in design and application.

The aim of our work is to devise techniques to continuously monitor GaN Power transistor parameters under hard-switching operation, and to investigate the role of switching transitions on device parameter drift. To this end, we have constructed a unique experimental setup while taking thermal management into account. The setup is capable of repeating the Double-Pulse Testing Technique multiple times and measuring device parameters in-situ as well as maintaining device temperature to avoid self-heating.

In summary, GaN transistors offer significant advantages in terms of switching reliability, especially in high-frequency and high-power applications. However, their successful deployment demands proper design, thermal management, and protection measures to ensure long-term performance and reliability in various electronic systems.

Low-Power Robot Platforms for Development of Energy-Efficient Algorithms for Pose Estimation, Mapping, and Activity Planning

J. Posada, S. Sudhakar, S. Karaman, V. Sze
Sponsorship: MIT Department of Aeronautics and Astronautics

Small-form autonomous robots are becoming quicker and more performant, giving them the potential to change the way we approach missions like environmental monitoring, search and rescue, and medicine. However, in order to enable long-duration missions, these robots must be extremely energy-efficient to compensate for their small batteries. Unlike in larger robotic systems, the energy spent sensing, mapping, estimating pose, and motion planning on small-form robots is comparable to energy spent on their actuators. In this work, we have used a small robotic car to begin collecting real-time computation and actuation power data using onboard power sensors and real-time pose data using a motion capture system. We have set a power consumption baseline for this autonomous robot of 0.41 W over a 0.60 W idle when moving at 0.32 m/s that will be used to compare the power consumption of different path-planning algorithms on a common platform. We will also test early-termination algorithms that stop computation on a path-planner early based on estimated energy consumption over execution of the path. Future work includes experiments using different path-planning and early-termination algorithms, and work on including computation energy in mapping and pose estimation algorithms optimized for total energy consumption. This research is novel in considering the energy consumption of computing hardware when optimizing path-planning algorithms for total energy consumption, and aims to demonstrate a new method for increasing the lifetime of severely energy constrained autonomous robots.

High-Speed Controllable Transformation Matching Network for Enhanced RF Power Delivery in Semiconductor Plasma Processes

K. N. Rafa Islam, D. J. Perreault

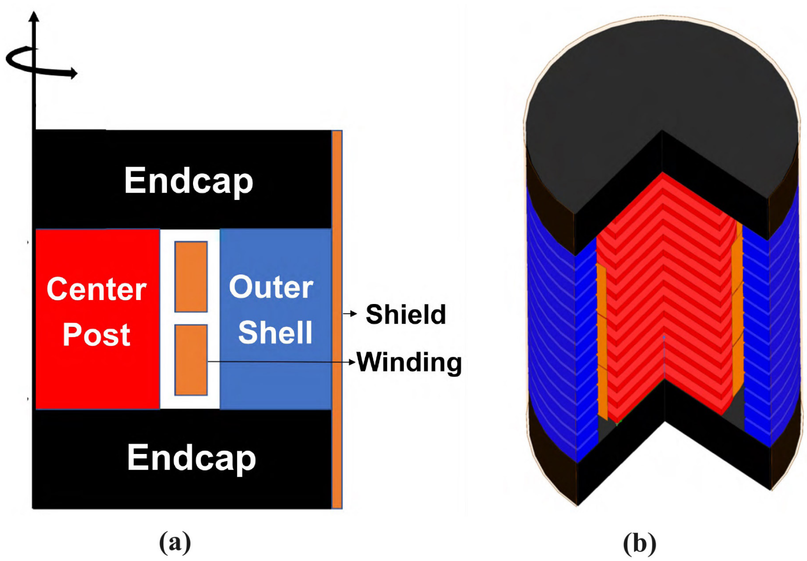
Efficient and controlled delivery of radio-frequency (rf) power for semiconductor plasma processing typically relies upon tunable matching networks to transform the variable plasma load impedance to a fixed impedance suitable for most rf power amplifiers. Plasma applications require fast tuning speed from the matching networks while operating at high frequency range. However, it is difficult to meet the requirements for many semiconductor plasma applications with conventional impedance matching solutions due to their limited response speeds. This slow speed comes from the presence of mechanical components in the matching network, since they can be tuned only mechanically. This work introduces a novel Controllable Transformation Matching Network (CTMN) intended to address the need for high-speed, tunable impedance matching. Here we show a controllable switching network at the core of the CTMN, leveraging switched-mode energy processing to provide high efficiency and exceptional control speed over a wide operational range.

The CTMN's design employs a two-port switching network coupled with a high-Q passive network, enabling rapid voltage adjustments and dynamic reactance tuning to swiftly accommodate both resistive and reactive load variations. Control strategies are introduced to maintain zero-voltage switching within the CTN as needed to minimize switching losses. This approach is substantiated through simulations, which indicates the CTMN's capability to achieve precise impedance matching with the potential for substantially faster response times (microseconds range) than traditional systems. It is anticipated that the proposed approach will enable ultra-fast, high-efficiency tunable impedance matching to address the needs of modern plasma systems.

High-Performance High-Power Inductor Design for High-Frequency Applications

M. V. Joisher , R. S. Bayliss, M. K. Ranjram, R. S. Yang, A. S. Jurkov, D. J. Perreault
Sponsorship: MKS instruments, Inc.

Magnetic components significantly impact the performance and size of power electronic circuits. This is especially true at radio frequencies (rf) of many MHz and above. As operating frequencies rise, the impact of losses in both copper and core becomes a substantial hurdle. Hence, in the high-frequency (HF, 3-30 MHz) range, coreless (or "air-core") inductors are conventionally preferred over cored magnetics. These inductors have typical Q (Quality factor: a measure of an inductor's efficiency) of 200-500 and are often the major contributor to a system's overall loss and size. Even when they can achieve high-Q, air-core inductors can induce electromagnetic interference (EMI) and eddy current loss in surrounding components, thus limiting system miniaturization. With recent advances in high frequency magnetic materials, there is interest in the design of cored inductors to achieve improved combinations of size and loss. This work investigates an approach to achieving high power, high-frequency, high-Q cored inductors. The proposed design approach leverages high-frequency magnetic materials, core geometry, quasi-distributed gaps, and a shield winding to realize high-frequency inductors that emit little flux outside their physical volume. Design guidelines for such inductors are introduced and experimentally verified with a 500 nH inductor (Q = 1150) designed to operate at 13.56 MHz with a peak ac current of up to 80 Amps. Such high-Q inductors can enhance the performance of the overall circuit and enable space-efficient designs for high-frequency high-power applications (e.g. rf plasma generation, HF wireless power transfer).



▲Figure 1: (a) Radial cross-section of the proposed inductor design, featuring the center post, outer shell, end caps, copper shield and a single-layer winding. (b) 3D model with a transparent shield and a pie cut out for better visibility.

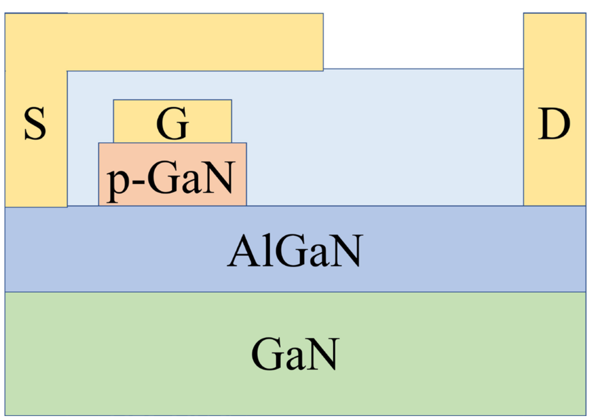
Gate Stack Design of p-GaN Gate GaN HEMTs

Y. Yu, J. A. del Alamo
Sponsorship: Texas Instruments

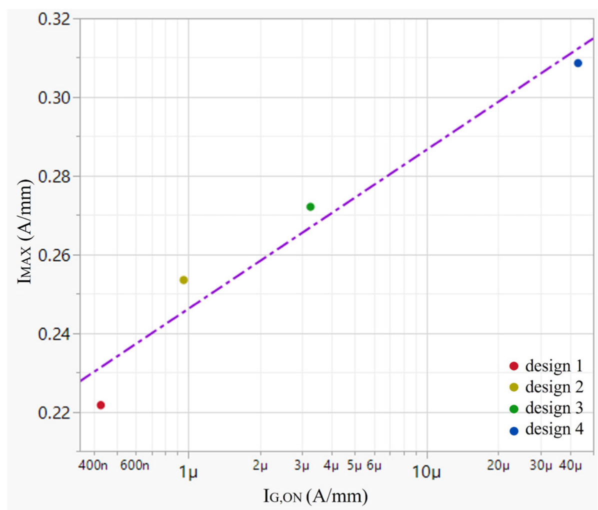
Gallium nitride (GaN) high electron mobility transistors (HEMTs) represent a significant advance in semiconductor technology, offering superior high-frequency and high-power capabilities. Despite their exceptional potential, the reliability of GaN HEMTs continues to be a critical challenge, particularly as it pertains to the variability in device behavior influenced by multiple factors including device scaling, thermal management, material defects, and susceptibility to electrical overstress. This study explores the reliability issues of p-GaN gate GaN HEMTs, the most promising structure for power management applications (Figure 1). In this work, we study the electrical characteristics of experimental transistors and correlate them with detailed characterization of specialized p-GaN test structures. In particular, we focus on understanding the impact of p-GaN gate design and fabrication process in transistor performance and reliability.

Our current experimental results suggest a strong connection between p-GaN gate process and electrical performance metrics, especially a trade-off between the peak saturation drain current (I_{MAX}) and ON-state current ($I_{G,ON}$). Generally, a gate design that yields a higher I_{MAX}, also results in higher $I_{G,ON}$. However, relatively modest process changes can result in large swings in I_{MAX} over 40% and $I_{G,ON}$ over two orders of magnitude (Figure 2). Our current studies of specialized test structures focus on understanding the origin of this phenomenon so as to synthesize device and process design guidelines.

The significance in this work extends beyond improving performance and reliability of GaN HEMTs. Our work aims to develop predictive models that can guide future GaN device design and fabrication techniques.



▲ Figure 1: Cross-sectional view of p-GaN gate GaN HEMT.



▲ Figure 2: Trade-off between I_{MAX} and $I_{G,ON}$ through four differently designed wafers.

Quantum Science and Engineering

Readout of a Transmon Qubit Using a Directional Readout Resonator with Interference Purcell Suppression

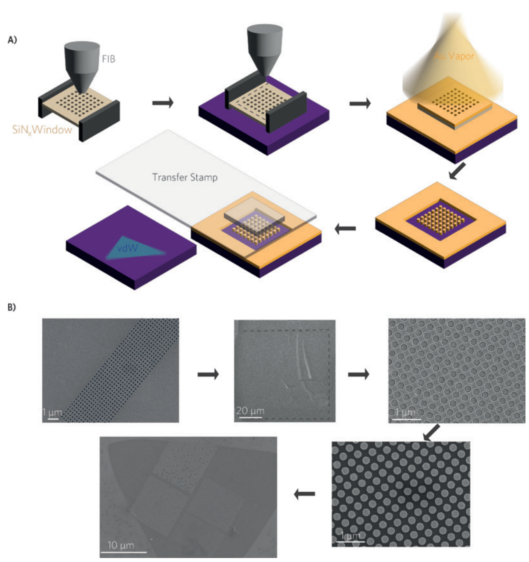
A. Yen, Y. Ye, K. Peng, J. Wang, G. Cunningham, M. Gingras, B. M. Niedzielski, H. Stickler, K. Serniak, M. Schwartz, K. O'Brien
Sponsorship: NSF Graduate Research Fellowship, MIT-IBM Watson AI Lab

Impedance mismatch in the readout bus is a leading cause of high variance in measurement rate κ in superconducting quantum processors. Moreover, the addition of bulky and high-magnetic field circulators and isolators is often needed for impedance matching. In this work, we demonstrate transmission-based readout of a transmon qubit using a directional readout resonator. Whereas a typical readout resonator would have a sharp dip in $|S21|$ on resonance, our directional resonator demonstrates a dip of less than 1dB on resonance, thus closely preserving the 50-ohm readout bus. This both maximizes measurement efficiency and avoids needing a weakly-coupled port, a major source of impedance mismatch in many standard qubit readout schemes. To enable fast readout and reset, we propose a novel interference Purcell filter compatible with directional readout and demonstrate Purcell suppression by 2 orders of magnitude over a bandwidth of more than 600 MHz. This architecture is expected to facilitate more scalable and modular design of quantum processors.

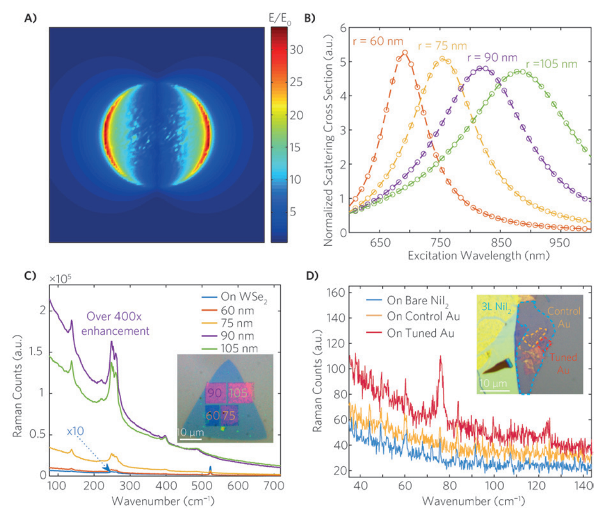
Transferable Optical Enhancement Nanostructures by Gapless Stencil Lithography

A.K. Demir, J.Li, T. Zhang, C. Occhialini, L. Nessi, J. Kong, R. Comin
Sponsorship: U.S. Department of Energy, Office of Science National Quantum Information Science Research Center's Co-design Center for Quantum Advantage (C2QA) contract DE-SC0012704, Raith VELION FIB-SEM in the MIT.nano Characterization Facilities (Award: DMR-2117609), MathWorks Science Fellowship (Award: 4000182189)

Optical spectroscopy techniques are central for the characterization of the electronic properties and symmetry of two-dimensional (2D) quantum materials. However, the reduced volume of atomically thin, micron-sized samples often results in a cross section that is far too low for conventional optical methods to produce measurable signals. In this work, we developed a scheme based on the stencil lithography technique to fabricate transferable high-resolution optical enhancement nanostructures for Raman and photoluminescence spectroscopy (Figure 1). Equipped with this new nanofabrication technique, we designed and fabricated plasmonic nanostructures to tailor the interaction of few-layer materials with light. We demonstrate an orders-of-magnitude increase in the Raman intensity of ultrathin flakes of 2D semiconductors and magnets (Figure 2) as well as selective Purcell enhancement of quenched excitons in WSe_2/MoS_2 heterostructures. We provide evidence (Figure 2d) that the method is particularly effective for optical studies of air-sensitive materials, as the fabrication and the transfer can be performed in situ. The fabrication technique can be easily generalized to enable a high degree of flexibility for functional photonic devices and surfaces.



▲Figure 1: Fabrication steps with corresponding SEM/FIB images. SiNx membranes are milled, flipped, and lowered to contact the substrate. The window is removed, and the material is evaporated. After the membrane lift-off, the nanostructures can be transferred onto the sample.



▲Figure 2: Raman enhancement due to transferred plasmonic arrays. A, Illustration of electric field enhancement due to a single gold nanodisk. B, Wavelength-dependent normalized scattering cross sections for various radii. C, Raman spectra of WSe_2. D, Raman spectra of three-layer NiI_2.

FURTHER READING

- J. -H. Hsia, J. A. Perozek, and T. Palacios, "First Demonstration of Optically-Controlled Vertical GaN finFET for Power Applications," *IEEE Electron Device Letters*, vol. 45, no. 5, pp. 774-777, May 2024. doi: 10.1109/LED.2024.3375856

High-Temperature Nanowire-Based Superconducting Circuits

D. J. Paul, D. Santavicca, K. K. Berggren
Sponsorship: NSF Engineering Research Center for Quantum Networks, MIT Lincoln Lab SNSPD Array Program

Superconducting electronics are promising for energy-efficient computing beyond CMOS, cryogenic sensor readout, and future quantum computing platforms. Among various families of superconducting circuits, nanowire-based cryotrons have proven to be quite useful in applications, including serving as pre-amplifiers for superconducting nanowire single-photon detector (SNSPD) readout, interfacing JJ-based circuits with CMOS circuits, functioning as digital logic circuits, and superconducting memory cells. These nanowire-based cryotrons are three-terminal devices which are immune to stray magnetic fields and capable of driving high-impedance loads while providing a high fan-out of digital signals. However, their operation has been demonstrated primarily in low-Tc material systems such as NbN, NbTiN, MoN, and WSi, resulting in their operating temperatures usually below 10K. However, in quantum communication and computing, there is a growing need to reduce thermal loads at the 4K or mK stage to accommodate more space for qubits and vacancy centers. This can be achieved by shifting cryogenic logic, memory, and microwave circuits to the 40K stage.

In this work, we investigate the performance of nanocryotrons fabricated on a thin film of YBCO with a critical temperature of 93K. Since the critical temperature of YBCO degrades when exposed to humidity and temperature, fabricating nanowires on YBCO without degrading its superconducting property is quite challenging. Additionally, YBCO does not react to commonly used reactive ion gases employed in etching. We will discuss how to address these challenges in the fabrication process of sub-100 nm width nanowires and present the current-voltage characteristics of the fabricated devices at 40K. Furthermore, we will explore how the device performance changes with increasing operating temperature, and then we will discuss how this work can pave the way for transitioning superconducting nanowire-based devices from sub-4K operation to a more affordable and compact liquid N_2 dewar setup.

Effects of Helium-ion Exposure on Superconducting-nanowire Single Photon Detectors

F. Incalza, M. Castellani, E. Batson, O. Medeiros, K. K. Berggren
Sponsorship: National Science Foundation (NSF) CQN Center

Ultra-fast single-photon detectors can be useful for applications including quantum optical communication systems, high-speed communication, lightweight cryogenics for space crafts and biomedical use. In particular, high-temperature superconductors can allow for the development of superconducting-nanowire single-photon detectors (SNSPDs) that can operate at higher temperatures than standard superconductors, enhancing the efficiency, simplicity of use, viability, and affordability of the device. Unfortunately, the fabrication of high-temperature superconducting nanowires damages the material. Moreover, the realization of large and uniform detector arrays formed by hundreds or thousands of detectors is fraught with complexities. As a result, the opportunity to modify the detector metrics through post-processing is attractive.

In this work, the effects of helium ion irradiation on superconductive nanowires single photon detectors are systematically investigated. We exposed NbN single nanowires and SNSPDs with a total active area of 5 x 5 μm^2, 8 x 8 μm^2, 10 x 10 μm^2 to a range of irradiation doses from ~ 10^{14} to ~ 10^{20} ions/cm^2 and thus demonstrated the impact of different doses on the target materials as well as improved the detector metrics. With an applied dose of $2.6 \cdot 10^{17}$ ions/cm^2, we were able to obtain an increase in the detector count rate of around a factor of 5. These results lead to the possibility of reaching homogeneous detector metrics after fabrication and on the same chip. This capability suggests the potential to achieve uniform and consistent detector performance across an entire chip, offering a solution to the challenge of creating large, high-quality detector arrays.

High Frequency Microwave Packaging for Josephson Traveling Wave Parametric Amplifiers

J. Wang, A. Yen, K. Peng, W. Van De Pontseele, K. Sliwa; P. Harrington, J. Qiu, K. Serniak, M. E. Schwartz, J. A. Formaggio, W. D. Oliver, K. P. O'Brien
Sponsorship: NSF Graduate Research Fellowship, the US DOE Office of Nuclear Physics (DE-FOA-0002110), the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz

The detection of single-photon microwave signals above 12 GHz is of significant interest for quantum sensing applications in neutrino mass measurement, dark matter searches, and quantum information processing. Below 12 GHz, quantum-limited amplification can be achieved with high-gain, broadband, and low-noise Josephson traveling wave parametric amplifiers (JTWPAs). However, standard microwave packaging for JTWPAs introduce package modes above 12 GHz, as well as impedance mismatches at the connectors and wirebonding locations that hinder the performance of JTWPAs. Here we present an approach to high frequency microwave package design that optimizes package and connector modes, minimizes wirebonds on interposer chips, and employs signal-line compensation strategies for better impedance matching throughout. The package is modular, easily prototyped, and is well-matched up to 27 GHz. This package will be deployed with a K band JTWPA tailored to the Project 8 neutrino mass measurement experiment, which will enable the detection of cyclotron radiation from single electrons with a signal-to-noise ratio improvement of an order of magnitude compared to current HEMT amplifiers. Since this design features low reflection and minimal spurious modes over a broad range of frequencies, this package can also be tailored to suit a wide range of superconducting quantum devices.

A Superconducting Bridge Rectifier Using the Asymmetric Surface Barrier Effect

M. Castellani, O. Medeiros, A. Buzzi, R. A. Foster, M. Colangelo, K. K. Berggren
Sponsorship: Department of Energy, National Laboratory LAB 21-2491 Microelectronics grant

Superconducting nanowire single-photon detectors (SNSPDs) arrays are currently being explored for quantum communication, bio-imaging, and space exploration. To enhance the scalability of such arrays based on niobium nitride (NbN) thin films, on-chip integration of nanowire-based control electronics is essential. In particular, a superconducting diode can be helpful for signal rectification and biasing. The superconducting diode effect (SDE) has been demonstrated with several technologies but integrating them into NbN-based systems can be challenging due to platform incompatibility. The asymmetric Bean-Livingston surface barrier effect in thin-film micro-bridges under external magnetic fields provides a potential solution. The effect has been observed in NbN wires with limited reproducibility. Moreover, half-wave rectification at more than 100 kHz and multi-diode circuits have never been shown. Overcoming these limitations would make it easier to construct more complex structures, like an AC-to-DC converter. The latter can assist in lowering the number of cables exiting the cryostat by frequency multiplexing the bias levels of several superconducting devices on chip.

We fabricated superconducting diodes by creating a lithographic triangular defect on one side of 1-µm wide NbN micro-bridges. By applying a 4-mT magnetic field, we observed the SDE with a 42% rectification efficiency at 4.2 K. We used these devices to demonstrate a bridge rectifier for full-wave rectification of 3-MHz sinusoidal signals, and AC-to-DC current conversion at 50 MHz, with an estimated 50% power efficiency. Additionally, we simulated a bias distribution network for SNSPDs with frequency-multiplexed bias levels by exploiting AC-to-DC converters based on the superconducting bridge rectifier. This proof-of-concept work demonstrates the possibility of designing complex circuits with superconducting diodes, paving the way for the scalability of SNSPD arrays and other superconducting systems.

FPGAs for Electrical Characterization of Superconducting Nanowire Based Circuits

R. A. Foster, O. Medeiros, K. K. Berggren
Sponsorship: DOE FNAL Microelectronics, DoD NDSEG Fellowship, Alan L McWhorter Fund Fellowship

Superconducting nanowire-based computing devices have the potential to play a crucial role in environments that demand extreme power efficiency, radiation hardness, and resilience to magnetic fields. Memory is a critical component of any computing system; thus, the current lack of scalable high-performance superconducting memory is a critical challenge to overcome. Superconducting Nanowire Memory (nMem) technology is a promising solution to this problem.

Current efforts to improve nMem designs and operation rely on expensive arbitrary waveform generators (AWGs) and oscilloscopes that are not well suited for parallelized memory cell tests or quickly providing high resolution analyses. Testing often involves large parameter space searches that take hours. Furthermore, the low memory capacity of the AWG greatly limits the resolution of our search space. Here, the AWG acts as the principal bottleneck.

An FPGA provides the necessary performance to increase parallelism without a proportional increase in cost, greatly improving testing resolution and speed and reducing test time from hours to seconds. In this project, we have developed a custom analog frontend to interface the FPGA with superconducting nanowires. Importantly, the flexibility of this system allows for a generalized application to any electronic system that demands a specialized testing procedure involving arbitrary signal processing and generation. The money, time, and energy that this innovation will save on validating cryogenic electronics in general will significantly improve our progress in developing these technologies.

Superconducting Nanocryotrons for Single-photon Detector Readout

A. Simon, O. Medeiros, F. Incalza, K. K. Berggren
Sponsorship: Department of Energy Fermi National Accelerator Laboratory Microelectronics (DE-AC02-07CH11359), MIT Vanu Bose Presidential Fellowship, NSF Graduate Research Fellowship (2141064), Department of Defense National Defense Science and Engineering Graduate Fellowship.

Efficient, low-noise single-photon detection is crucial to sensing, communication, and computing applications. To date, superconducting nanowire single-photon detectors (SNSPDs) are the most efficient such detectors, with the lowest dark count rates and shortest timing jitter in the ultraviolet to infrared (IR) wavelengths.

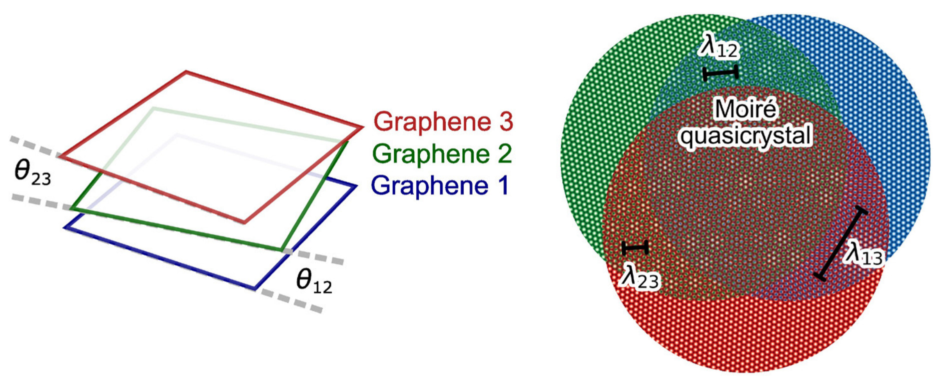
Many applications require detection in the mid-IR. However, the read-out signal from SNSPDs produced for these wavelengths is usually weaker than for ultraviolet and visible detectors. Consequently, detection at longer wavelengths necessitates a low-noise, low-energy cryogenic amplifier. High-electron-mobility transistors and cryogenic complementary metal-oxide semiconductor amplifiers can provide amplification, yet they are not scalable due to substantial power dissipation and a lack of integrability with SNSPDs. In contrast, superconducting nanocryotron (nTron) devices provide gain with minimal power dissipation and are easily integrated on-chip with SNSPDs, making them ideal candidates for these purposes.

To optimally amplify SNSPD pulses, nTron devices must provide consistent and maximal gain. Due to heterogeneous current density across nTrons, the location of the nTron choke is a salient design parameter for determining the device's gain. Thus, to ascertain the best choice of choke offset position we have fabricated a wafer with 350 nTron devices and measured their switching characteristics. We are currently working to determine the gain of each device as a function of the location of the choke to develop a model for the optimal nTron design for SNSPD read-out. This design will then improve the performance of SNSPDs in mid-IR and array applications.

Superconductivity and Strong Interactions in a Tunable Moiré Quasicrystal

A. Uri, S. C. de la Barrera, M. T. Randeria, D. Rodan-Legrain, T. Devakul, P. J. D. Crowley, N. Paul, K. Watanabe, T. Taniguchi, R. Lifshitz, L. Fu, R. C. Ashoori, P. Jarillo-Herrero
Sponsorship: MIT Pappalardo Fellowships, Israel CHE Outstanding Postdoctoral Fellowship in Quantum Science and Technology, Army Research Office MURI, NSF, STC Center for Integrated Quantum Materials, Gordon and Betty Moore Foundation's EPiQS Initiative.
This work was performed in part at the Harvard University Center for Nanoscale Systems, a member of the National Nanotechnology Coordinated Infrastructure Network, JSPS KAKENHI, the Israel Science Foundation

Electronic states in quasicrystals generally preclude a Bloch description, rendering them fascinating and enigmatic. Owing to their complexity and scarcity, quasicrystals are underexplored relative to periodic and amorphous structures. Here, we introduce a new type of highly tunable quasicrystal easily assembled from periodic components. By twisting three layers of graphene with two different twist angles, we form two mutually incommensurate moiré patterns. In contrast to that in many common atomic-scale quasicrystals, the quasiperiodicity in our system is defined on moiré length scales of several nanometres. This "moiré quasicrystal" allows us to tune the chemical potential and thus the electronic system between a periodic-like regime at low energies and a strongly quasiperiodic regime at higher energies, the latter hosting a large density of weakly dispersing states. Notably, in the quasiperiodic regime, we observe superconductivity near a flavor-symmetry-breaking phase transition, the latter indicative of the important role that electronic interactions play in that regime. The prevalence of interacting phenomena in future systems with in-situ tunability is not only useful for the study of quasiperiodic systems but may also provide insights into electronic ordering in related periodic moiré crystals. We anticipate that extending this platform to engineer quasicrystals by varying the number of layers and twist angles and by using different two-dimensional components will lead to a new family of quantum materials to investigate the properties of strongly interacting quasicrystals.



▲Figure 1: Left, three layers of graphene stacked with two different twist angles. Right, every pair of layers (1-2, 2-3, and 1-3) forms an interference moiré pattern with a unique wavelength **λ**. For given twist angles, the different wavelengths are in general incommensurate, forming a novel "moiré quasicrystal."

FURTHER READING

- A. Uri, S. C. de la Barrera, M. T. Randeria, D. Rodan-Legrain, T. Devakul, P. J. D. Crowley, N. Paul, K. Watanabe, T. Taniguchi, R. Lifshitz, L. Fu, R. C. Ashoori, and P. Jarillo-Herrero, "Superconductivity and Strong Interactions in aTunable Moiré Quasicrystal," *Nature,* vol. 620, pp. 762–767, 2023.

Probing Kinetic Inductance in Thin Niobium Diselenide ($NbSe_2$) through Microwave Measurements

S. Zaman, J. I-J. Wang, M. Tanaka, T. Werkmeister, M. Hays, D. R. Legrain, A. Goswami, T. Dinh, M. Gingras, B. M. Niedzielski, H. Stickler, M. E. Schwartz, J. L. Yoder, K. Watanabe, T. Taniguchi, T. P. Orlando, J. A. Grover, S. Gustavsson, K. Serniak, P. Jarillo-Herrero, P. Kim, W. D. Oliver
Sponsorship: MIT RLE, MIT EECS, MIT Lincoln Laboratory, Department of Applied Physics, Harvard University, Research Center for Functional Materials, International Center for Materials Nanoarchitectonics

We developed hybrid superconducting microwave resonators incorporating van der Waals (vdW) superconductors to explore the MW response of superconducting 2D materials in the GHz regime. We first developed a reliable technique to contact thin $NbSe_2$, entirely encapsulated with hexagonal Boron Nitride (hBN), with a coplanar Al resonator. Then we fabricated a hybrid Al-$NbSe_2$ resonator and measured the kinetic inductance of thin $NbSe_2$. We report a kinetic inductance of 5 layers of $NbSe_2$ of 0.3 nH/□. Crystalline 2D superconductors with high kinetic inductance can be used in superconducting quantum devices, photon detection, and other quantum sensors.

This research was funded in part by the US Army Research Office grant no. W911NF-2210023, by the National Science Foundation QII-TAQS grant no. OMA-1936263, and by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. S.Z. acknowledges support from the Schlumberger Foundation Faculty for the Future Fellowship. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the US Government.

Research Centers

Center for Integrated Circuits and Systems

Associate Professor Ruonan Han, Director

The Center for Integrated Circuits and Systems (CICS) at MIT, established in 1998, is an industrial consortium created to promote new research initiatives in circuits and systems design, as well as to promote a tighter technical relationship between MIT's research and relevant industry. Eight faculty members participate in the CICS: Director Ruonan Han, Hae-Seung (Harry) Lee, Anantha Chandrakasan, Song Han, David Perreault, Negar Reiskarimian, Charles Sodini, and Vivienne Sze.

CICS investigates circuits and systems for a wide range of applications, including artificial intelligence, wireless/wireline communication, sensing, security, biomedicine, power conversion, quantum information, among others.

We strongly believe in the synergistic relationship between industry and academia, especially in practical research areas of integrated circuits and systems. CICS is designed to be the conduit for such synergy.

CICS's research portfolio includes all research projects that the eight participating faculty members conduct, regardless of source(s) of funding, with a few exceptions.

Technical interaction between industry and MIT researchers occurs on both a broad and individual level. Since its inception, CICS recognized the importance of holding technical meetings to facilitate communication among MIT faculty, students, and industry. We hold two full-day technical meetings per year open to CICS faculty, students, and representatives from participating companies. Throughout each meeting, faculty and students present their research, often presenting early concepts, designs, and results that have not been published yet. The participants then offer valuable technical feedback, as well as suggestions for future research. The meeting also serves as a valuable networking event for both participants and students. Closer technical interaction between MIT researchers and industry takes place through the projects of particular interest to participating companies. Companies may invite students to give on-site presentations, or they may offer students summer employment. Additionally, companies may send visiting scholars to MIT or create a separate research contract for more focused research for their particular interest. The result is truly synergistic, and it will have a lasting impact on the field of integrated circuits and systems.

MIT/MTL Center for Graphene Devices and 2-D Systems

Professor Tomás Palacios, Director

The MIT/MTL Center for Graphene Devices and 2-D Systems (MIT-CG) brings together MIT researchers and industrial partners to advance the science and engineering of graphene and other two-dimensional (2-D) materials.

Two-dimensional materials are revolutionizing electronics, mechanical and chemical engineering, physics and many other disciplines thanks to their extreme properties. These materials are the lightest, thinnest, strongest materials we know of. At the same time that they have extremely rich electronic and chemical properties. MIT has been leading research on the science and engineering of 2-D materials for more than 40 years. Since 2011, the MIT/MTL Center for Graphene Devices and 2-D Systems (MIT-CG) has played a key role in coordinating most of the work going on at MIT on these new materials, and in bringing together MIT faculty and students, with leading companies and government agencies interested in taking these materials from a science wonder to an engineering reality.

Specifically, the Center explores advanced technologies and strategies that enable 2-D materials, devices, and systems to provide discriminating or breakthrough capabilities for a variety of system applications ranging from energy generation/storage and smart fabrics and materials to optoelectronics, RF communications, and sensing. In all these applications, the MIT-CG supports the development of the science, technology, tools, and analysis for the creation of a vision for the future of new systems enabled by 2-D materials.

Some of the many benefits of the Center's membership include complimentary attendance to meetings, industry focus days, and live webcasting of seminars related to the main research directions of the Center. Our industrial members also gain access to a resume book that connects students with potential employers, as well as access to timely white papers on key issues regarding the challenges and opportunities of these new technologies. There are also numerous opportunities to collaborate with leading researchers on projects that address some of today's challenges for these materials, devices, and systems.

The MIT Medical Electronic Device Realization Center

Professor Charles Sodini, Co-Director
Professor Thomas Heldt, Co-Director

The vision of the MIT Medical Electronic Device Realization Center (MEDRC) is to revolutionize medical diagnostics and treatments by bringing health care directly to the individual and to create enabling technology for the future information-driven healthcare system. This vision will, in turn, transform the medical electronic device industry. Specific areas that show promise are wearable or minimally invasive monitoring devices, medical imaging, portable laboratory instrumentation, and the data communication and associated analysis and reasoning algorithms.

Rapid innovation in miniaturization, mobility, and connectivity will revolutionize medical diagnostics and treatments, bringing health care directly to the individual. Continuous monitoring of physiological markers will place capability for the early detection and prevention of disease in the hands of the consumer, shifting to a paradigm of maintaining wellness rather than treating sickness. Just as the personal computer revolution has brought computation to the individual, this revolution in personalized medicine will bring the hospital lab and the physician to the home and to the site of emergency situations. From at-home cholesterol monitors that can adjust treatment plans, to cell phone-enabled blood labs, these system solutions containing state-of-the-art sensors, electronics, and computation will radically change our approach to health care. This new generation of medical systems holds the promise of delivering better quality health care while reducing medical costs.

The revolution in personalized medicine is rooted in fundamental research in microelectronics from materials to sensors, to circuit and system design. This approach has already fueled the semiconductor industry to transform society over the last four decades. It provided the key technologies to continuously increase performance while constantly lowering cost for computation, communication, and consumer electronics. The processing power of current smart phones, for example, allows for sophisticated signal processing to extract information from this sensor data. Data analytics can combine this information with other patient data and medical records to produce actionable information customized to the patient's needs. The aging population, soaring healthcare costs, and the need for improved healthcare in developing nations are the driving force for the next semiconductor industry's societal transformation, Medical Electronic Devices.

The successful realization of such a vision also demands innovations in the usability and productivity of medical devices, and new technologies and approaches to manufacturing devices. Information technology is a critical component of the intelligence that will enhance the usability of devices; real-time image and signal processing combined with intelligent computer systems will enhance the practitioners' diagnostic intuition. Our research is at the intersection of Design, Healthcare, and Information Technology innovation. We perform fundamental and applied research in the design, manufacture, and use of medical electronic devices and create enabling technology for the future information-driven healthcare system.

The MEDRC has established a partnership between microelectronics companies, medical device companies, medical professionals at Boston-area hospitals, and MIT to collaboratively achieve needed radical changes in medical device architectures, enabling continuous monitoring of physiological parameters such as cardiac vital signs, intracranial pressure, and cerebral blood flow velocity. A visiting scientist from a project's sponsoring company is present at MIT. Ultimately this individual is the champion that helps translate the technology back to the company for commercialization and provide the industrial viewpoint in the realization of the technology. MEDRC projects have the advantage of insight from the technology arena, the medical arena, and the business arena, thus significantly increasing the chances that the devices will fulfill a real and broad healthcare need as well as be profitable for companies supplying the solutions. With a new trend toward increased healthcare quality, disease prevention, and cost-effectiveness, such a comprehensive perspective is crucial.

In addition to the strong relationship with MTL, MEDRC is associated with MIT's Institute for Medical Engineering and Science (IMES) that is charged to serve as a focal point for researchers with medical interest across MIT. MEDRC has been able to create strong connections with the medical device and microelectronics industry, venture-funded startups, and the Boston medical community. With the support of MTL and IMES, MEDRC serves as the catalyst for the deployment of medical devices that will reduce the cost of healthcare in both the developed and developing world.

Faculty Profiles

Anuradha M. Agarwal

Principal Research Scientist
Materials Research Laboratory Leader
FUTUR-IC: Sustainable Microchip Manufacturing
LEAP: Lab for Education and Application Prototypes Electronic Photonic Packaging/ Heterogenous Integration

Sustainable materials and device designs for microchip manufacturing and use; Planar, integrated, Si-CMOS-compatible microphotonics platform for on-chip MIR hyperspectral imaging and chem-bio sensing applications; radiation effects on silicon microphotonics; non-linear materials and devices; aerosol detection; mid-infrared detectors, electronic-photonic packaging; heterogenous integration.

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SELECTED PUBLICATIONS

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SELECTED PUBLICATIONS

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SELECTED PUBLICATIONS

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RECENT PUBLICATIONS

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T. Butruille, J.C. Crone, and C. M. Portela, "Decoupling Particle-impact Dissipation Mechanisms in 3D Architected Materials," *Proc. Natl. Acad. Sci.* 121 (2024)

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SELECTED PUBLICATIONS

A. Chandrasekhar, R. Padrós-Valls, R. Pallares-Lopez, E. Palanques-Tost, N. Houstis, T. M. Sundt, H.-S. Lee, C. G. Sodini, and A. D. Aguirre, "Tissue Perfusion Pressure Enables Continuous Hemodynamic Evaluation and Risk Prediction in the Intensive Care Unit," *Nature Medicine*, vol. 29, no. 8, pp. 1998-2006.

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P. Z. X. Li, S. Karaman, and V. Sze, "GMMap: Memory-Efficient Continuous Occupancy Map Using Gaussian Mixture Model," *IEEE Transactions on Robotics (T-RO)*, Vol. 40, pp. 1339 – 1355, Jan. 2024.

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A. Kachkine and L. F. Velásquez-García, "High-Performance, Low-Cost, Additively Manufactured Electrospray Ion Sources for Mass Spectrometry," *J. of the American Society for Mass Spectrometry*, Vol. 35, No. 5, pp. 862–870, May 2024. doi: 10.1021/jasms.3c00409

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SELECTED PUBLICATIONS

L.-Y. Yu, and S. You, "High-Fidelity and High-Speed Wavefront Shaping by Leveraging Complex Media," *Science Advances*, arXiv preprint arXiv:2302.10254. 2024

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Theses Awarded

S.B.

- **Katherine Lei** (P. ANIKEEVA)
  Functionalization Platform of Magnetic Nano Materials through Silica Shell Formation
- **Nikita Romanov** (R. HAN)
  Edge-Radiating CMOS Sub-THz Phased Array

S.M.

- **Henry Andersen** (J. LANG)
  Modeling, Manufacturing, and Experimental Validation of an Electric Machine for Aircraft Propulsion
- **H. Azzouz** (D. ENGLUND)
  Second Harmonic Generation in Silicon Photonic Crystal Resonator for Quantum Optic Applications
- **Adina Bechhofer** (L. DANIEL)
  Geometrical Optimization of Planar Nano Vacuum Channel Transistors
- **Mercer Boris** (L. DANIEL)
  AI in the Cath Lab: Implications of Clinical AI-Enabled Assistance for Intravascular Ultrasound Procedures
- **Honghao Cao** (S. YOU)
  Adaptive Fiber Source for Label-free Nonlinear Microscopy
- **Jakie Chen** (L. DANIEL)
  Clustering of Similar Incident Tickets Using Natural Language Processing
- **S. Corsetti** (J. NOTAROS)
  Visible-Light Integrated Photonics for 3D-Printing and Trapped-Ion Systems
- **Marc Davis** (D. ENGLUND)
  Numerical Synthesis of Arbitrary Multi-qubit Unitaries with Low T-count
- **Connor Gerlach** (S. YOU)
  Non-diffracting Beam for Microscopy
- **Isaac Harris** (D. ENGLUND)
  Hyperfine Interactions of the Group IV Color Centers
- **A. Hattori** (J. NOTAROS)
  Integrated-Photonics Devices and Architectures for Advanced Cooling of Trapped Ions
- **Lauren Heintz** (L. DANIEL)
  Scenario Analysis of Profitability of New Offerings under Different Business Contract Models
- **Jung-Han (Sharon) Hsia** (T. PALACIOS)
  Optically Controlled Vertical GaN finFET for Power Applications
- **Steven Hubbard** (D. BONING)
  Empowering Delivery Service Partners: A Study on Leveraging Generative Artificial Intelligence and Text Clustering to Support External Partners
- **Ryan Kochert** (D. BONING)
  Process Digitalization: 3D Deep Learning in Manufacturing Applications
- **Mingyuan Li** (D. BONING)
  Cost Analysis and Process Optimization of Electrochemical Micromachining for Volume Manufacturing
- **Kunzan Liu** (S. YOU)
  Deep and Dynamic Metabolic Imaging
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  Autonomous Drone Assisted Aircraft Inspections
- **Mikala N. Molina** (L. DANIEL)
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- **Rachel Owens** (D. BONING)
  Dynamic Time Warping Constraints for Semiconductor Processing
- **Sarah Spector** (F. NIROUI)
  Nonplanar Nanofabrication via Interface Engineering
- **Grace Tang** (J. LANG)
  Designing an Efficient Power/Control System for a Network of Piezoelectric Speakers
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  Analysis of Data from the U.S. Shipbuilding Industry and Application to Improve Performance Metrics
- **Zi Yu Fisher Xue** (V. SZE)
  Accelerating Sparse Tensor Algebra by Overbooking Buffer Occupancy
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  Design/System Technology Co-optimization of Gallium Nitride High Electron Mobility Transistors for Next-G 3DIC Heterogeneous Integration of Gallium Nitride and Si CMOS
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  Kinetic Inductance Characterization of Thin 2H-NbSe2 Superconductor Using Circuit Quantum Electrodynamics

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Glossary

TECHNICAL ACRONYMS

ADC	Analog-to-Digital Converters
CMOS	Complementary Metal–Oxide–Semiconductor
CNT	Carbon Nanotubes
ECP	Electro-Chemical Plating
FET	Field-Effect Transistor
HSQ	Hydrogen Silsesquioxane
InFO	Integrated Fan Out
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
nTRON	Nanocryotron
RDL	Re-distribution Layers
RIE	Reactive Ion Etching
SNSPDs	Superconducting Nanowire Single Photon Detectors
SS	Subthreshold Swing
TMAH	Tetramethylammonium Hydroxide
TREC	Thermally Regenerative Electrochemical Cycle

MIT ACRONYMS & SHORTHAND

BE	Department of Biological Engineering
Biology	Department of Biology
ChemE	Department of Chemical Engineering
CICS	Center for Integrated Circuits and Systems
CMSE	Center for Materials Science and Engineering
↳**IRG**	Interdisciplinary Research Group
DMSE	Department of Materials Science & Engineering
EECS	Department of Electrical Engineering & Computer Science
ISN	Institute for Soldier Nanotechnologies
KI	David H. Koch Institute for Integrative Cancer Research
LL	Lincoln Laboratory
MAS	Program in Media Arts & Sciences
MechE	Department of Mechanical Engineering
MEDRC	Medical Electronic Device Realization Center
MIT-CG	MIT/MTL Center for Graphene Devices and 2D Systems
MITEI	MIT Energy Initiative
MIT-GaN	MIT/MTL Gallium Nitride (GaN) Energy Initiative

MISTI	MIT International Science and Technology Initiatives
MIT-SUTD	MIT-Singapore University of Technology and Design Collaboration Office
MIT Skoltech	MIT Skoltech Initiative
MTL	Microsystems Technology Laboratories
NSE	Department of Nuclear Science & Engineering
Physics	Department of Physics
Sloan	Sloan School of Management
SMA	Singapore-MIT Alliance
↳**SMART**	Singapore-MIT Alliance for Research and Technology Center
↳**SMART-LEES**	SMART Low Energy Electronic Systems Center
SUTD-MIT	MIT-Singapore University of Technology and Design Collaboration Office
UROP	Undergraduate Research Opportunities Program

U.S. GOVERNMENT ACRONYMS

AFOSR	U.S. Air Force Office of Scientific Research
↳**FATE-MURI**	Foldable and Adaptive Two-dimensional Electronics Multidisciplinary Research Program of the University Research Initiative
AFRL	U.S. Air Force Research Laboratory
ARL	U.S. Army Research Laboratory
↳**ARL-CDQI**	U.S. Army Research Laboratory Center for Distributed Quantum Information
ARO	Army Research Office
ARPA-E	Advanced Research Projects Agency - Energy (DOE)
DARPA	Defense Advanced Research Projects Agency
↳**DREaM**	Dynamic Range-enhanced Electronics and. Materials
DoD	Department of Defense
DoE	Department of Energy
↳**EFRC**	U.S. Department of Energy: Energy Frontier Research Center (Center for Excitonics)
DTRA	U.S. DoD Defense Threat Reduction Agency
IARPA	Intelligence Advanced Research Projects Activity
↳**RAVEN**	Rapid Analysis of Various Emerging Nanoelectronics
NASA	National Aeronautics and Space Administration
↳**GSRP**	NASA Graduate Student Researchers Project
NDSEG	National Defense Science and Engineering Graduate Fellowship
NIH	National Institutes of Health
↳**NCI**	National Cancer Institute
NNSA	National Nuclear Security Administration

NRO	National Reconnaissance Office
NSF	National Science Foundation
↳**CBMM**	NSF Center for Brains, Minds, and Machines
↳**CIQM**	Center for Integrated Quantum Materials
↳**CSNE**	NSF Center for Sensorimotor Neural Engineering
↳**E3S**	NSF Center for Energy Efficient Electronics Science
↳**GRFP**	Graduate Research Fellowship Program
↳**IGERT**	NSF The Integrative Graduate Education and Research Traineeship
↳**NEEDS**	NSF Nano-engineered Electronic Device Simulation Node
↳**PECASE**	Presidential Early Career Awards for Scientists and Engineers
↳**SEES**	NSF Science, Engineering, and Education for Sustainability
↳**STC**	NSF Science-Technology Center
ONR	Office of Naval Research

OTHER ACRONYMS

CNRS Paris	Centre National de la Recherche Scientifique
CONACyT	Consejo Nacional de Ciencia y Tecnología (Mexico)
IEEE	Institute of Electrical and Electronics Engineers
IHP Germany	Innovations for High Performance Microelectronics Germany
KIST	Korea Institute of Science and Technology
KFAS	Kuwait Foundation for the Advancement of Sciences
MASDAR	Masdar Institute of Science and Technology
NTU	Nanyang Technological University
NUS	National University of Singapore
NYSCF	The New York Stem Cell Foundation
SRC	Semiconductor Research Corporation
↳**NEEDS**	NSF/SRC Nano-Engineered Electronic Device Simulation Node
SUTD	Singapore University of Technology and Design
TEPCO	Tokyo Electric Power Company
TSMC	Taiwan Semiconductor Manufacturing Company

Principal Investigator Index

IN APPRECIATION OF OUR
MICROSYSTEMS INDUSTRIAL GROUP MEMBER COMPANIES:

Analog Devices
Applied Materials
Draper
Edwards
Ericsson
GlobalFoundries
Hitachi High-Tech Corporation
IBM
Lam Research Corp.
Lockheed Martin
muRata
NEC Corporation
Soitec
Taiwan Semiconductor Manufacturing Company
Texas Instruments

AND MIT.NANO CONSORTIUM MEMBER COMPANIES:

Analog Devices, Inc.
Applied Materials
Edwards
Fujikura
IBM Research
Lam Research
Lockheed Martin
NC
NEC Corporation
Shell
UpNano
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MTL MICROSYSTEMS TECHNOLOGY LABORATORIES

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