MARC2023

Microsystems Annual Research Conference

January 24 – 25, 2023
Omni Mount Washington Resort
New Hampshire

MARC2023

MICROSYSTEMS ANNUAL RESEARCH CONFERENCE

JANUARY 24–25, 2023 • BRETTON WOODS, NH

"Metamorphosis to a New Era of Innovative Microsystems"

Massachusetts Institute of Technology

MTL MICROSYSTEMS TECHNOLOGY LABORATORIES

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Microsystems Technology Laboratories Annual Expo 2023

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PDF version, January 2023

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INTRODUCTION

Dear colleagues,

Welcome to MARC 2023! We're delighted to have you back for our first in-person conference since 2020. Though the effects of the global pandemic still persist today, we are grateful for the myriad of ways our community has remained connected over the past two years: virtual gatherings at MARC 2021 and 2022, the success of both remote and hybrid research collaborations, and above all, the care and patience for each other that help us persevere through trying times.

We come together today to celebrate the scientific and technological achievements of the past year, to revisit and redefine our roles as researchers in ever-shifting sociopolitical contexts, and to acknowledge the precious and resilient community that we have built and maintained together. This conference would not have been possible without the indefatigable efforts of our Student Committee, MTL and MIT.nano staff, the current and former directors of MTL, Prof. Tomás Palacios and Prof. Hae-Seung (Harry) Lee, and MIT.nano director Prof. Vladimir Bulović. We would like to extend our heartfelt thanks to this team.

With that, it is our honor to introduce MARC 2023. After a MARC-themed social activity and dinner banquet on the first day, we are excited to welcome our first keynote speaker. Eileen Tanghal is the founder and general partner of Black Opal Ventures and former managing director at In-Q-Tel. Her keynote and fireside chat will bring together her unique perspectives as "Engineer, VC, Mother, Spy" on investing for the greater good. On our second day, we are excited to welcome Dr. Ann Kelleher, who is the executive vice president and general manager of technology development at Intel Corporation. With her extensive experience in leading R&D for next generation silicon chip technologies, she will provide critical perspectives on the future of the semiconductor industry in this crucial time of the recent global chip shortage and the CHIPS and Science Act.

MARC 2023 features over 100 student abstracts spanning 40 research groups. On the morning and afternoon of the second day, students will present their research in technical blocks consisting of 60-second pitches and poster sessions. During lunch, we will feature MIG/MAP member pitches and offer students time to interact 1-on-1 with MIG/MAP members. We would like to thank our members, as well as the abstract authors, participants, and volunteers for their sponsorship and support of our event.

We wish you an enjoyable MARC2023! We hope that you will take this opportunity to strengthen friendships, forge new connections, and think upon our conference theme this year: metamorphosis to a new era of innovative microsystems.

Best,

Jenn Wang and Maitreyi Ashok
MARC2023 Co-Chairs

AGENDA

DAY 1: JANUARY 24

7:00am	**Early Bus Departs MIT** 60 Vassar Street, Cambridge, MA
10:00am - 4:00pm	**Winter Activities** Bretton Woods, NH
12:00pm	**Late Bus Departs MIT** 60 Vassar Street, Cambridge, MA
3:00pm - 5:00pm	**Check-in & Registration** Great Hall Conference check in @ MARC2023 Registration Desk Hotel check-in @ Hotel front desk *(Rooms available after 4pm)*
5:00pm - 6:00pm	**Welcome Reception** Conservatory
6:00pm - 6:30pm	**Opening Remarks** Grand Ballroom *Team Building Activity*
6:30pm - 7:30pm	**Dinner Banquet** Grand Ballroom
7:30pm - 8:45pm	**Evening Keynote: Eileen Tanghal** Grand Ballroom
8:45pm - 9:00pm	**Group Photo** Grand Ballroom
9:00pm - 12:00am	**Evening Activities** Washington, Jefferson & Reagan Rooms *Dessert and coffee will be served.*
9:00pm - 10:45pm	**Pitch Practice and AV Check** Grand Ballroom

AGENDA

DAY 2: JANUARY 25

8:00am - 9:00am	**Breakfast** Main Dining Room Meal vouchers distributed at MARC2023 Registration Desk.
9:00am - 9:15am	**Opening Remarks** Grand Ballroom
9:15am - 10:00am	**Technical Keynote: Dr. Ann Kelleher** Grand Ballroom
10:00am - 10:15am	**MIG/MAP Pitches** Grand Ballroom
10:15am - 10:30am	**Morning Break** Grand Ballroom Lobby
10:30am - 10:45am	**MIG/MAP Pitches** Grand Ballroom
10:45am - 11:45am	**60 Second Poster Pitches (Sesson 1)** Grand Ballroom • Electronic Devices • Integrated Circuits • Medical Devices & Biotechnology • Power
11:45am - 12:45pm	**Poster Session 1** Conservatory
12:45pm - 2:00pm	**MIG/MAP Networking Lunch** Main Dining Room
2:00pm - 3:00pm	**60 Second Poster Pitches (Sesson 2)** Grand Ballroom • Materials & Manufacturing • Nanotechnology & Nanomaterials • Optics & Photonics • Quantum Technologies
3:00pm - 4:00pm	**Poster Session 2 / Coffee Break** Conservatory
4:00pm - 4:30pm	**Closing Ceremony** Grand Ballroom
4:30pm - 5:00pm	**Buses Depart to MIT** Hotel Main Entrance

DAY 1: KEYNOTE

EILEEN TANGHAL

Founder & General Partner
Black Opal Ventures

Eileen Tanghal is a venture capitalist with nearly 20 years of experience. She has been involved with and sat on the boards of over 40 high tech startup companies in the US and Europe as a financial venture capitalist, corporate venture capitalist, and now as Founder and General Partner of Black Opal Ventures. Black Opal is focused on investing in companies looking to revolutionize healthcare through the utilization of advanced technology including Artificial Intelligence/Machine Learning, Computing at the Edge, TinyML Digital Twins and Novel Sensors. Prior to Black Opal, Eileen served as the Managing Director of IN-Q-TEL's London office, and before that, Eileen was Vice President of New Business Ventures at ARM Holdings and Global Head of Applied Matierals in-house venture capital fund, Applied Ventures. Eileen holds a Bachelor of Science in Electrical Engineering and Computer Science from MIT and went on to receive her MBA from London Business School. Outside of being a venture capitalist, she owns and operates theCoderSchool Fremont and theCoderSchool Redwood City. She has a passion for advancing the number of women in the STEM and venture capital fields.

DR. ANN KELLEHER

Executive Vice President & General Manager of Technology Development
Intel Corporation

Dr. Ann Kelleher is the executive vice president and general manager of Technology Development at Intel Corporation. Since 2020, she is responsible for the research, development and deployment of the next-generation silicon, advanced packaging, and test technologies that power Intel's innovation. She joined Intel in 1996 as a process engineer and has worked in areas spanning from litho, thin films, yield, to managing all of Intel's Global operations including Fab and Assembly Test factories, supply chain and construction. She did her Ph.D. in electrical engineering from University College Cork in Ireland and her post-doc at IMEC.

INDUSTRY CONSORTIUM (MIG & MAP)

Analog Devices, Inc.	Lam Research Corp.
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IBM	UpNano

From its very inception, MIT has maintained an intimate connection with industry to inform and inspire its research endeavors. The Microsystems Industrial Group (MIG), established in the early ‘80s, proved to be an effective platform for engagement of industry with the MTL community! The launch of MIT.nano in 2018 defines a new chapter in MIT’s history for advancing science and technology at the nanoscale. Since 2020, the flagship Microsystems Annual Research Conference (MARC) has been co-hosted by MTL and MIT.nano. It is our distinct pleasure to welcome all of our industry partners to join us again at MARC2023.

ABSTRACTS

SESSION 1: ELECTRONIC DEVICES

SESSION 2: INTEGRATED CIRCUITS

SESSION 3: MEDICAL DEVICES & BIOTECHNOLOGY

SESSION 4: POWER

SESSION 5: MATERIALS & MANUFACTURING

SESSION 6: NANOTECHNOLOGY & NANOMATERIALS

SESSION 7: OPTICS & PHOTONICS

SESSION 8: QUANTUM TECHNOLOGIES

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Research Interests:
2D materials, Electronic devices, Electronics, Energy, Energy harvesting devices & systems, III-Vs, Light-emitting diodes, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Photovoltaics, Quantum devices.

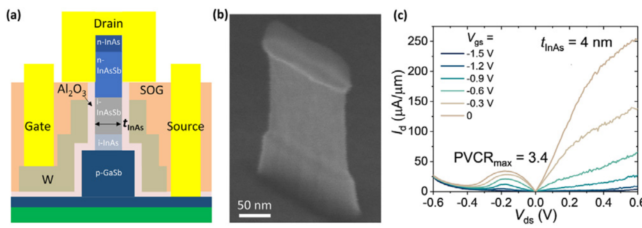
Ultra-scaled III-V Vertical Nanofin Broken-band Tunnel FETs

1.02

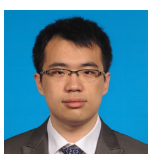
Y. Shao, J. A. del Alamo
Sponsorship: Intel Corporation

Tunnel FETs (TFETs) have attracted great attention due to their ability to operate with a sub-thermal subthreshold swing (S), which promises significant reduction in supply voltage and static power consumption in logic circuits. III-V materials are of particular interest in designing TFETs, thanks to the flexibility of band engineering and their superior transport properties. Looking forward, stringent logic transistor scaling forces a sub-5-nm critical dimension, which requires a detailed study of the potential of TFETs in this strong quantum-confinement regime.

In this work, we fabricate a set of vertical fin (VF) GaSb/InAs broken-band Esaki diodes and TFETs through a top-down approach down to sub-5-nm-wide fins. Negative differential resistance is clearly observed. An average on-state current exceeding 200 μA/μm at $|V_{ds}| = 0.3$ V and an average minimum subthreshold swing of 140 mV/dec are demonstrated in the ultra-scaled devices. Strikingly, quantum confinement is shown to improve the band-to-band tunneling dramatically. This work shows the great potential of ultra-scaled III-V VF TFETs as future CMOS transistors.



▲ (a) Schematic of the VF TFET cross-sectional view. (b) SEM image of a *t*InAs = 4 nm VF, covered by 3 nm Al_2O_3 on each of the sidewall. (c) Output characteristics of a VF TFET with *t*InAs = 4 nm.



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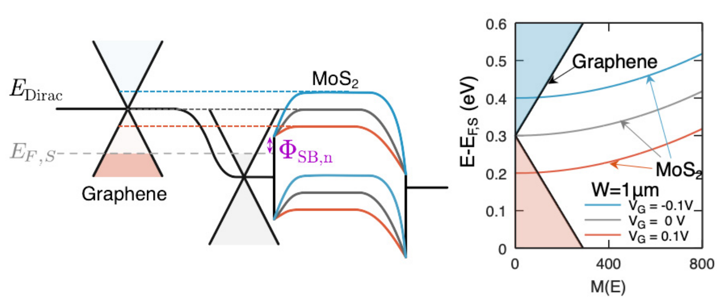
Research Interests:
2D materials, Electronic devices, Electronics, Nanomaterials, Nanotechnology.

Cold-Source FET with Graphene/MoS_2 Heterojunction

1.03

P. Wu, X. Ji, J. Kong
Sponsorship: MIT Lincoln Laboratory Advanced Concept Committee

Transistors with steep subthreshold slopes (SS) are of interest for reducing the supply voltage and thus the power consumption of integrated circuits. However, existing steep-slope device concepts, such as tunnel FET (TFET), nanoelectromechanical (NEM) relay and impact-ionization MOSFET (I-MOS), have limitations in terms of on-current, switching speed, reliability, etc. In this work, we investigate cold-source field-effect transistor (CS-FET) based on graphene/MoS_2 heterojunction as a candidate for steep slope transistor, which relies on low-pass energy filtering from the graphene source to enable cold carrier injection. Since no band-to-band tunneling (BTBT) is involved in the transport, CS-FET could potentially achieve higher on-current than TFET. We study chemical vapor deposition (CVD) synthesis of in-plane stitched graphene-MoS_2 heterojunction as a route to reduce the contact length between the graphene source and the MoS_2 channel and minimize the rethermalization of the cold carriers caused by inelastic scattering. We demonstrate a baseline local-bottom-gated MoS_2 FET without graphene source that exhibits SS of 70mV/dec, highlighting the excellent electrostatic gate control. Finally, we discuss possible strategies to further scale down contact length, providing a guideline for realization of CS-FET.



▲ Band diagram and number of modes of a graphene/MoS_2 CS-FET.

Uniform High-Aspect-Ratio GaN Vertical Sub-30-nm-Diameter Nanowires Formed by Optimized Two-Step Etching Process

1.05

P.-C. Shih, T. Palacios

Sponsorship: AFOSR through MURI Empty State Electronics Project

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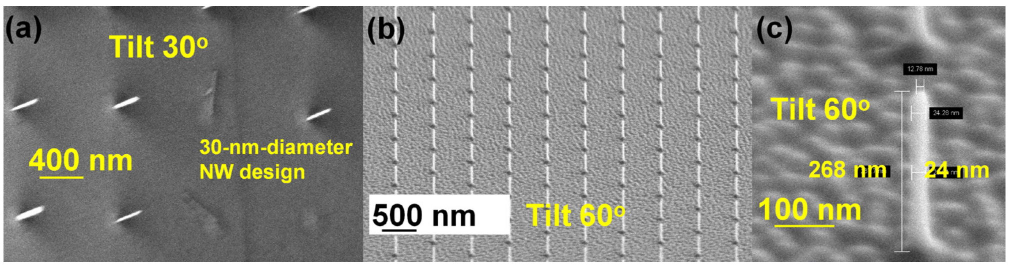
Research Interests:
2D materials, Electronic devices, Electronics, Energy harvesting devices & systems, Field-Emitter devices, GaN, III-Vs, Lasers, Light-emitting diodes, Nanomanufacturing.

III-Nitride semiconductors are key enablers of many applications, including optoelectronics, power electronics, and RF amplifiers. However, so far, III-Nitride vertical structures with sub-100 nm dimensions still face yield and uniformity issues, limiting III-Nitrides' impact in nanostructure devices and product. In this project, we optimized the plasma etching process for GaN, and combine it with the subsequent wet-based digital etching (DE) to demonstrate uniform and high-yield GaN sub-30-nm-diameter vertical nanowires (NWs) with high aspect-ratio (> 11:1). We are currently investigating the effects of this approach on material damage and device defects. This new technology is expected to advance future development on III-Nitride nanoelectronics and optoelectronics, for example, vertical NWs for water splitting (for fuel generation) and vertical NW transistors.



▲ Band diagram and number of modes of a graphene/MoS2 CS-FET.

Monolithically Integrated Gallium Nitride Complementary Technology for All-GaN Multi-Functional Chips

1.06

Q. Xie, J. Niroula, P. Yadav, M. Yuan, N. Chowdhury, T. Palacios

Sponsorship: Samsung Electronics Co., Ltd., Qualcomm, Inc., Intel Corp.

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The rising performance of GaN power ICs has offered compactness, and record levels of efficiency and power for data centers, power adapters, electric vehicles (EVs), and 5G telecommunication systems. However, the lack of a practical GaN p-FET introduces major limitations: (1) significant static power dissipation (resulting from the use of n-type enhancement-mode/depletion-mode logic); (2) a roadblock towards all-GaN integration (e.g. control loops, analog mixed-signal blocks). Furthermore, the availability of high-side switching GaN p-FETs would circumvent the switching speed bottleneck (limited common-mode transient immunity (CMTI) in the level shifter), therefore enabling more efficient power converters.

In recent years, extensive research has been pursued at MIT in the emerging domain of GaN complementary technology, which features: (1) integration of p-FET and n-FET on the same platform without the need of regrowth of III-N material; (2) scalable platform for eventual commercialization; (3) ability to withstand the large heat generation in EVs, data centers, and base stations; (4) high p-FET and n-FET performance. The reported progress has been enabled by a combination of new device structures (e.g. self-aligned p-FinFET) and process optimization (e.g. techniques to reduce etch-induced damage). Current research effort is focused on advancing device-level performance and exploration of novel GaN complementary circuits.

Use of Ion Implantation to Engineer the Electric Field Profiles in GaN Superjunctions

1.07

M. Oh, J. Perozek, J. Hsia, T. Palacios

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Research Interests:
Electronic devices, Electronics, GaN, III-Vs, Integrated circuits, MEMS & NEMS, Nanomanufacturing, Nanomaterials, Nanotechnology, Si.

Power electronics play a significant role in various applications, such as power grids and electric vehicles. Power transistors are required to block high voltages while having a low resistance to reduce power consumption during operation. Gallium Nitride (GaN) is highly promising in this context due to its wide bandgap and excellent transport parameters compared to other semiconductors such as Si. Additionally, superjunction structures consisting of alternating n- and p-type columns have significantly improved the performance of Si-based power transistors, since they can overcome the limitation on the trade-off between high breakdown voltage and low ON resistance. However, GaN vertical superjunctions have never been reported so far due to the difficulties in the epitaxial growth and fabrication.

In this work, the feasibility of fabricating GaN superjunctions through ion implantation is explored through simulation. Stopping and Range of Ions in Matter (SRIM) is used to acquire the estimated Si doping profiles in p-GaN substrate for several sets of ion implantation parameters. Technology Computer Aided Design (TCAD) simulation is conducted using Silvaco ATLAS simulator with the doping profiles from SRIM to verify the two-dimensional electric field profiles in the superjunction structure. Finally, the technical challenges that are not considered in the simulation are discussed.

High Performance P-type 2D Transistors with Low Resistance Contacts

1.08

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Sponsorship: Intel (ISRA)

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Research Interests:
2D materials, Electronic devices, Electronics, Energy, Energy harvesting devices & systems, Integrated circuits, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics.

Among all the emerging materials, two-dimensional (2D) semiconductors appear to be promising for the next generation electronics due to their atom layer thickness, relatively wide band gap and high mobility. Whereas numerous research has been focused on n-type 2D semiconductors, e.g. molybdenum disulfide (MoS_2), in the past decades, p-type 2D materials, e.g. tungsten diselenide (WSe_2), have not been explored sufficiently, which have equal importance in building 2D complementary metal-oxide-semiconductor (CMOS) circuits. In particular, reducing the contact resistance between a p-type 2D channel and a metal contact to a silicon transistor-comparable level is essential to achieve a high-performance p-type transistor.

In this work, we demonstrate a high-performance p-type WSe_2 transistor with palladium (Pd) contacts. Monolayer WSe_2 film is directly synthesized on SiO_2/Si substrate using metal organic chemical vapor deposition (MOCVD). Pd contacts are sequentially formed with molecular beam epitaxy (MBE) technique, at a high vacuum level (3×10^{-10} Torr). This allows an ultra-clean interface between the WSe_2 and Pd, which results in low contact resistance. Moreover, we analyze the quality of contacts formed at different pressure levels by two different methods, i.e. using MBE and conventional electron beam evaporation (10^{-6}~10^{-7} Torr). This research on high-performance p-type 2D transistor with reduced contact resistance will be an important step for the using 2D materials in CMOS circuits. For future work, we will expand our research on ohmic contact by exploiting semi-metal contacts which can reduce metal-induced gap states (MIGS) between semiconductors and contact materials.

Small-Signal Capacitance-Voltage Characteristics of Ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ Structures in the GHz Regime

1.09

T. Kim, J. Grajal, D. A. Antoniadis, and J. A. del Alamo

Sponsorship: Semiconductor Research Corporation (2020-LM-3000), Samsung Electronics

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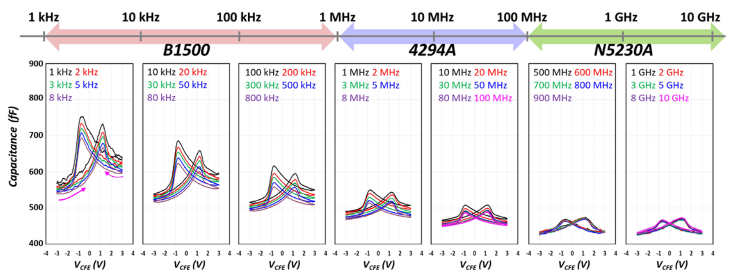
Research Interests:
2D materials, Artificial Intelligence, Displays, Electronic devices, Electronics, III-Vs, Integrated circuits, Nanomanufacturing, Nanomaterials, Nanotechnology, Si, Thermal structures, devices & systems.

Due to its domain dynamics, the butterfly shape is the unique capacitance-voltage (C-V) curve signature of Metal-Ferroelectric-Metal (MFM) structures. Small-signal characterization of the MFM structure in the GHz regime is critical to the design of high-frequency ferroelectric (FE) devices, such as varactor diodes, tunable filters, and phase shifter. However, although several reports show the RF characteristics, it is unclear how the C-V characteristics change in the GHz regime. These are difficult measurements due to the need for a specialized device layout and an accurate de-embedding process for the parasitics.

In this work, we have for the first-time measured the small-signal C-V characteristics of FE Hf0.5Zr0.5O2 MFM structures over a broad frequency range, from 1 kHz to 30 GHz. These devices were fabricated on high bandwidth coplanar waveguides. An accurate de-embedding process and the extraction of an equivalent circuit model enabled us to obtain the intrinsic C-V curves in the GHz range. Remarkably, we observe that the butterfly-shaped curve persists in the GHz range and becomes more symmetric and saturated with respect to frequency. This work will contribute to understanding small-signal FE dynamics in the GHz regime.



◄ (a) C-V characteristics of intrinsic FE $Hf_{0.5}Zr_{0.5}O_2$ MFM structures in a coplanar waveguide configuration measured from 1 kHz to 10 GHz.

Heterogeneous Integration of GaN and Si for MMICs above 300 GHz, 6G Applications and Beyond

1.10

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

Sponsorship: AFOSR, Lockheed Martin Corporation

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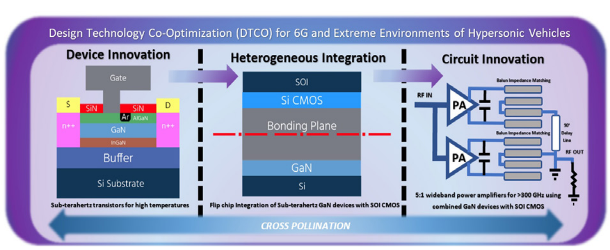
Research Interests:
Communications, Electronic devices, Electronics, GaN, Integrated circuits, Nanomanufacturing, Nanomaterials, Nanotechnology, Si, Systems.

The future of Gallium Nitride (GaN) radio frequency (RF) circuit technology is at the intersection of material synthesis, device modelling, and circuit design. Currently, these are three separate fields with little-to-no communication between them, resulting in critical limitations to today's technology. There is an urgent need for these fields to collaborate, cross-pollinate, and intersect in order to modernize and advance innovation for the next generation of RF circuits.

To design the most efficient RF and mmWave circuits, we must embrace the design-technology co-optimization (DTCO) approach, as described in fig. 1, that combines new GaN-based transistors with engineered linearity, novel heterogeneous integration with state-of-the-art Silicon (Si) BEOL control circuits, and advanced physics-based modeling. This project sets the foundation of the next generation of RF and mixed signal circuits for applications such as 6G and the extreme environments of hypersonic vehicles.



◄ (a) Plan for development of novel transistors and high frequency, wideband power amplifiers targeting the >300 GHz Spectrum with heterogeneous integration of GaN and Silicon.

Low-temperature Synthesis of Monolayer MoS_2 on 200-mm Silicon Platform

1.11

J. Zhu, J.-H. Park, S. A. Vitale, J. Wang, M. Mohamed, T. Zhang, M. Xue, X. Zheng, Z. Wang, J. Kong, T. Palacios

Sponsorship: Ericsson

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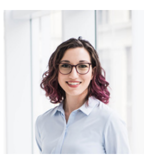
Research Interests:
2D materials, Electronic devices, Electronics, Energy harvesting devices & systems, GaN, III-Vs, Integrated circuits, Nanomaterials, Nanotechnology, Sensors, Si, SiGe and Ge.

Two-dimensional materials, such as MoS_2, have attracted great attention in the past decade and are being considered as promising candidates for the next-generation heterogeneous electronic and photonic systems. There have also been many demonstrations of wafer-scale synthesis, e.g., 2-inch or 4-inch, of monolayer MoS_2. However, the chemical vapor deposition (CVD) or metal-organic chemical vapor deposition (MOCVD) methods proposed so far require high growth temperature (> 600°C), which is not compatible with silicon back-end-of-line (BEOL) integration unless an additional wafer-scale transfer process is used. This makes the heterogenous integration of 2D materials and silicon very difficult.

In this work, we demonstrate, for the first time, 8-inch MoS_2 monolayer thin film grown at 275°C by the MOCVD method. The short growth time (40-70 mins), in combination with the low thermal budget, allows direct silicon BEOL- compatible integration without any transfer process. The synthesized MoS_2 demonstrates good wafer-level uniformity and does not degrade the silicon transistors underneath. This novel low-temperature synthesis method paves the way for heterogenous integration of 2D materials with silicon circuits, allowing the higher-density integration needed in the next-generation of electronics, e.g., ubiquitous intelligence and industrial internet.

Integration and Evaluation of SiN and Al_2O_3 as Passivation and Gate-dielectrics in GaN HEMTs

1.12



G. Micale, R. Ley, T. Palacios, B. Briggs

Sponsorship: Applied Materials

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Research Interests:
Electronic devices, GaN, III-Vs, Lasers, Light-emitting diodes, Optoelectronics, Photonics, Photovoltaics, Sensors, Si, SiGe and Ge.

Increasing power demands of modern technology has motivated the switch to wide bandgap semiconductors for power devices. With a critical electric field 11 times larger than that of Si, GaN is well suited for high-power electronics. While high-power GaN devices have already begun commercialization, high-volume manufacturing and device performance remain key areas of interest for developing the technology. Switching to Si substrates from the traditionally used SiC offers greater production scaling and significant cost reductions. For GaN high electron mobility transistors (HEMTs) defects on the AlGaN surface create charging effects that degrade the current linearity and contribute to threshold voltage instability. Implementing surface passivation reduces the density of defects and their related electronic trap states and improves the stability of the device. Another significant challenge GaN HEMTs face is gate leakage characteristic to Schottky-gated devices under high forward bias. Adding a dielectric to the gate region and creating a metal-insulator-semiconductor (MIS) gate structure is an effective way to reduce this gate leakage. Consequently, MISHEMT devices exhibit lower power consumption and better breakdown characteristics over Schottky-gated HEMTs.

Since GaN lacks a high-quality native oxide, careful consideration must be taken in designing and integrating the dielectric for passivated and MIS-gate GaN HEMTs. In this work, we investigate the roles of SiN and Al_2O_3 as passivation and gate dielectrics in GaN on Si depletion-mode HEMTs. We begin with studying the passivation effects of each dielectric on Schottky-gate HEMTs, noting the improvement to current collapse over un-passivated devices. Then, by creating a MIS structure in the gate region, we measure the performance of MISHEMTs to evaluate the integration of both dielectrics and the quality of the dielectric-semiconductor interface.

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Available from June 2025.

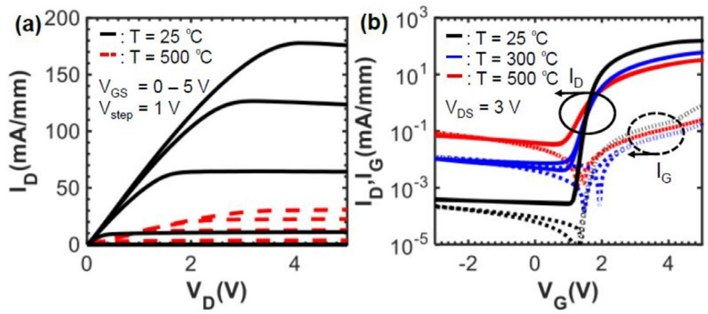
Research Interests:
Electronic devices, Electronics, Energy, Energy harvesting devices & systems, GaN, III-Vs, Integrated circuits, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics, Quantum devices, Thermal structures, Devices & systems.

High Temperature RF GaN Electronics

1.13

J. Niroula, Q. Xie, P. Yadav, T. Palacios
Sponsorship: AFOSR, Lockheed Martin

High temperature electronics has received much interest recently due to emerging applications in geothermal well exploration, hypersonic flight electronics, and space exploration. GaN based devices are an exciting contender for extremely high temperature environments due to their high mobility, high saturation velocity, especially beyond 250°C, which is the limit of traditional silicon-based devices. In this project we aim to develop a high performing GaN based RF device that operates at both room temperature as well as 500°C, by developing high temperature refractory T-gates such as tungsten, high temperature gate barriers such as p-GaN, AlN, and Ga¬2O3 (Figure 1), and high temperature passivation such as AlN and GaN. Such high temperature ready devices will allow high performing RF communication systems operating in the extreme conditions needed to enable the aforementioned applications.



▲ Figure 1: Output (a) and Transfer (b) of p-GaN gated E-mode HEMTs at room temperature and 500°C

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Research Interests:
Electronic devices, Nanomaterials, Sensors.

Epitaxial Perovskite Ferroelectric Based Capacitive Memory

1.14

X. Zhang, M.-K. Song, C. S. Chang, S. Lee, J. Kim
Sponsorship: IARPA MicroE4AI Program

Nowadays, development of artificial intelligence requires more power efficient memory device. Compared to the conventional resistive memory, capacitive memory device is quite promising as it eliminates static power consumption and prevents IR drop by leveraging charge transfer. However, the widely used $Hf_{0.5}Zr_{0.5}O_2$ (HZO) is polycrystalline and has high coercive field, resulting in significant variations when scaled to nanoscale and high write energy. On the other hand, single-crystalline perovskite ferroelectric oxides like $BaTiO_3$ (BTO) have better uniformity and a coercive field 2~3 orders of magnitude lower than HZO. Furthermore, 100x higher dielectric constant can also enlarge the memory window. Previous study uses buffer layer for silicon compatibility, resulting in poor performance. This project investigates epitaxial perovskite ferroelectric material for energy-efficient, high performance and CMOS compatible capacitive memory device. Freestanding single-crystalline BTO is obtained by chemical lift-off technique using $Sr_3Al_2O_6$ as the sacrificial layer, then transferred onto polymer-coated silicon and fabricated into capacitors. Polarization switching in BTO film leads to a butterfly-like shape capacitance-voltage curve with 1.5V switching voltage. Asymmetric electrode is designed to achieve curve shift with an on/off ratio of 150% at zero bias. Both coercive voltage and memory window we proposed are better than HZO-based devices. It also shows stable performance with more than 1000 cycles of endurance and more than 1000s of retention. This capacitor memory device serves as a good element in crossbar array for next generation in-memory computing.

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Two-dimensional MoS_2 transistors and sensors

1.15

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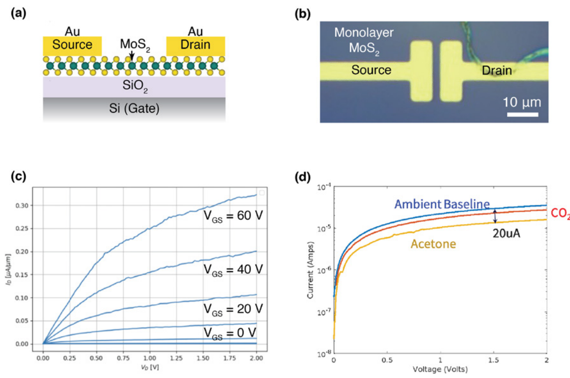
Sponsorship: MIT EECS, 6.2540 class

Wearable medical devices require flexible and conformable electronics. A flexible transistor is one of the core building blocks for the creation of such technologies. Here, we present a transistor based on two-dimensional (2D) molybdenum disulfide (MoS_2) monolayers. Thanks to its band gap and subnanometer thickness, monolayer MoS_2 can be used as a semiconductor in the fabrication of flexible transistors, exhibiting high on/off ratios and low power dissipation. Using gold-mediated transfer, we deposited a large area MoS_2 monolayer from its source natural crystal on to a silicon oxide-on-silicon substrate. We then patterned the desired source-drain electrodes lithographically forming the final structure shown in Figure 1a-b with a representative performance that is illustrated in Figure 1c. Due to the MoS_2 monolayer's high surface-to-volume ratio and sensitivity to various analytes, our developed transistor can also serve as a suitable sensing platform which we demonstrated for acetone and carbon dioxide as the results of Figure 1d show.



◀ Figure 1: a) Schematic illustration of the MoS_2 transistor design, b) An optical micrograph of a working transistor, c) Example I-V characteristic of the transistor, d) Sensing performance of the transistor.

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Research Interests:
2D materials, Machine Learning.

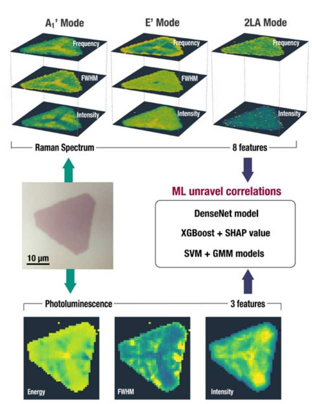
Unraveling the Correlation Between Raman and Photoluminescence in Monolayer MoS_2 through Machine Learning Models

1.16

A.-Y. Lu, L. G. Pimenta Martins, P.-C. Shen, Z. Chen, J.-H. Park, M. Xue, J. Han, N. Mao, M.-Hui Chiu, T. Palacios, V. Tung, J. Kong

Sponsorship: U.S. Army Research Office through the Institute for Soldier Nanotechnologies at MIT, under cooperative agreement number W911NF-18-2-0048

Photoluminescence (PL) is a crucial property for optoelectronic and photonic applications such as light-emitting diodes, photodetectors, and single-photon emitters. 2D transition metal dichalcogenides (TMDCs) are promising materials for next-generation devices due to their intense and tunable PL. Raman spectroscopy stands out among standard characterization tools for 2D materials as a fast and non-destructive technique capable of probing doping and strain. However, a comprehensive understanding of the correlation between PL and Raman spectra in MoS2 monolayers remains elusive due to its highly nonlinear nature. Here we have demonstrated a framework to capture the correlations through a collection of machine learning models. Our work may serve as a methodology for applying machine learning in 2D material characterizations and providing the knowledge for tuning and synthesizing 2D semiconductors for high-yield PL.



◀ A collection of machine learning techniques is utilized to effectively discover the hidden pattern between Raman- and PL-spectra of MoS_2, which provide insights into the physical mechanisms connecting PL and Raman features.

Session 2: Integrated Circuits

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Research Interests:
Artificial Intelligence, Electronics, Integrated circuits, Machine Learning, ML Accelerators.

Algorithm and Hardware Co-optimization for Image Segmentation in Wearable Ultrasound Devices

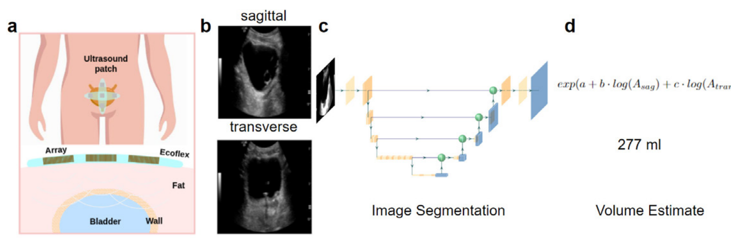
2.02

Z. Song, V.t Kumar, S. Ramaswamy, A. P. Chandrakasan

Sponsorship: Texas Instruments

Miniaturization of ultrasound devices enables wearable applications, where various tissues can be continuously monitored. Image segmentation is an essential step in its automation, such as in continuous bladder monitoring shown below. Processing the data in the cloud raises security and privacy concerns. On the other hand, processing the image on the edge faces stringent resource constraints: limited computation, memory, and total energy consumption.

In this work, an image segmentation model is binarized while maintaining clinically acceptable accuracy. To take full advantage of the lightweight algorithm, specialized hardware is developed. First, the power efficiency of the ASIC is optimized for recent NNs with smaller filter sizes and depthwise separable convolutions. Second, the ASIC addresses the unique challenges of image segmentation, specifically high peak SRAM usage. The specialized hardware will enable a new generation of smart wearable devices to facilitate medical diagnosis.



▲ Example application of the image segmentation accelerator in continuous bladder monitoring. (a)(b) An ultrasound patch collects images. c) An ASIC on the wearable device uses neural networks for segmentation. d) The bladder volume is calculated.

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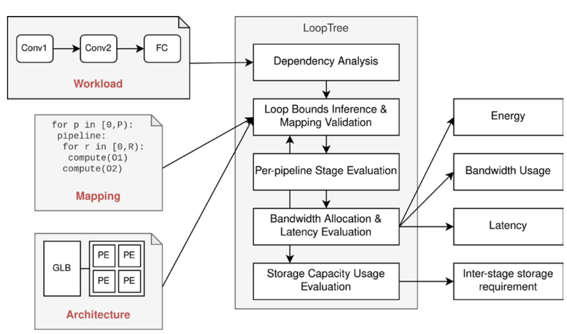
Exploration Framework for Pipelined Tensor Algebra Accelerator

2.03

M. Gilbert, N. Wu, A. Parashar, V. Sze, J. Emer

Sponsorship: MIT AI Hardware Program

In recent years many accelerators have been proposed to efficiently process tensor algebra workloads (e.g. neural networks). Architectures often process one kernel (e.g. convolution, fully connected, etc.) at a time. However, recent works have proposed optimization opportunities across cascaded kernels. This work presents LoopTree to help explore these optimizations. While prior mapping space explorations have been specific to the proposed architecture, LoopTree is a flexible representation that can describe various accelerators, workloads, and mapping of cascaded kernels. This work also presents a framework that takes the LoopTree representation and estimates latency, energy, bandwidth, and storage requirements. Cascaded-kernel accelerators employ optimized dependency-constrained pipelines. To model these pipelines, the framework is equipped with novel data dependency analysis, cascaded-kernel pipeline performance model, and inter-stage storage requirement analysis.



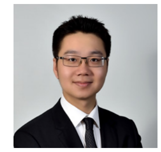
▲ High-level overview of LoopTree analysis flow.

Memory-Efficient Gaussian Fitting for Depth Images in Real Time

2.04

P. Z. X. Li, A. Wojtyna, S. Karaman, V. Sze

Sponsorship: NSF RTML 1937501, NSF CPS 1837212



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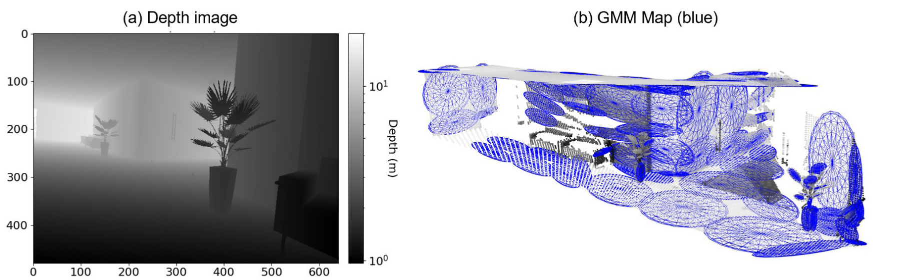
Research Interests:
Electronics, Integrated circuits, Systems, Robotics, Algorithm Hardware Co-design.

Constructing a compact representation for 3D environments in real time is essential for enabling autonomy on energy-constrained robots. During map construction, the memory usage is not limited to map storage, but also includes overheads for storing the sensor measurements and temporary variables. Prior works reduce the map size while incurring a large memory overhead (MBs) which increases energy consumption and limits throughput.

We present the Single-Pass Gaussian Fitting (SPGF) algorithm that accurately constructs a compact Gaussian Mixture Model (GMM) from a depth image. By processing one pixel at a time in a single pass through the image, SPGF achieves higher throughput and orders-of-magnitude lower memory overhead than prior multi-pass approaches. Using a low-power ARM Cortex-A57 CPU, SPGF operates at 32fps, requires 43KB of memory overhead, and consumes only 0.11J per image. Energy consumption can be further reduced by a fixed-point implementation of SPGF in specialized hardware.



▲ (a) An image from a depth camera, and (b) a GMM generated using the proposed SPGF algorithm with a RMSE of 9cm, a memory overhead of 43KB, a throughput of 32fps, and an energy consumption of 0.11 J per frame using the low-power ARM Cortex-A57 CPU.

On-Device Training Under 256KB Memory

2.05

J. Lin, L. Zhu, W.-M. Chen, W.-C. Wang, C. Gan, S. Han

Sponsorship: NSF, MIT-IBM Watson AI Lab, MIT AI Hardware Program, Amazon, Intel, Qualcomm, Ford, Google

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Research Interests:
Multimedia, Systems, Machine Learning, Computer Vision.

Deep learning inference has revolutionized various areas. On-device training further enables the model to adapt to new data collected from the sensors by fine-tuning a pre-trained model. Users can benefit from customized AI models without transferring the data to the cloud, protecting privacy. However, the training memory consumption is prohibitive for IoT devices with tiny memory resources. We propose an algorithm-system co-design framework to make on-device training possible with only 256KB of memory. On-device training faces two unique challenges: (1) the quantized graphs of neural networks are hard to optimize due to low bit-precision and the lack of normalization; (2) the limited hardware resource does not allow full back-propagation. To cope with the optimization difficulty, we propose Quantization-Aware Scaling to calibrate the gradient scales and stabilize 8-bit quantized training. To reduce the memory footprint, we propose Sparse Update to skip the gradient computation of less important layers and sub-tensors. The algorithm innovation is implemented by a lightweight training system, Tiny Training Engine, which prunes the backward computation graph to support sparse updates and offload the runtime auto-differentiation to compile time. Our framework is the first solution to enable tiny on-device training of convolutional neural networks under 256KB SRAM and 1MB Flash without auxiliary memory, using less than 1/1000 of the memory of PyTorch and TensorFlow while matching the accuracy on tinyML application VWW. Our study enables IoT devices not only to perform inference but also to continuously adapt to new data for on-device lifelong learning. A video demo can be found here: https://youtu.be/XaDCO8YtmBw.

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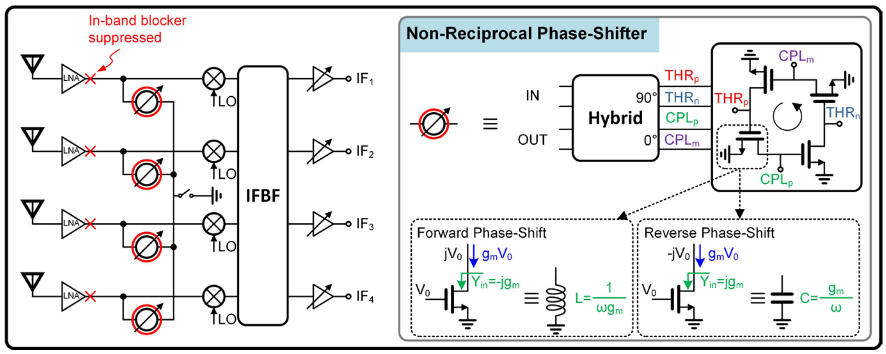
A mm-Wave N-Input-N-output MIMO Receiver with Non-Reciprocal Phase-Shifters for Spatial Notch Filtering

2.06

S. Mohin, S. Araei, N. Reiskarimian

Digital multiple-input multiple-output mm-wave receivers can provide multiple output data streams and flexible digital calibration. Also, digital beamformers require less area and power consumption than hybrid beamformers. But front-end components of digital beamformers are susceptible to blockers which limits their dynamic range and linearity performance.

In this work, we introduce non-reciprocal phase-shifters (NRPSs) to form a spatial notch filter right at the output of the low-noise amplifiers (LNAs). Due to the rejection of the blockers at the LNAs' outputs, the system linearity is significantly improved. In contrast to the conventional mm-wave spatial notch filters, NRPSs are located in auxiliary paths, thus can be disabled in the absence of blockers to reduce noise and power consumption. Any digital beamformer can be enhanced with NRPS to strengthen its resilience to spatial blockers, making it an attractive candidate for 5G new radio (NR) frequency range 2 (FR2) applications.



▲ Block diagram of the proposed architecture

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Research Interests:
Communications, Electronics, Integrated circuits, Systems.

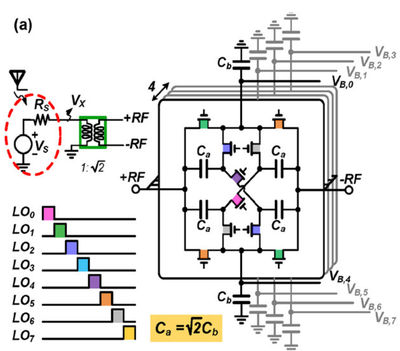
An Interferer-Tolerant Harmonic-Resilient Receiver with Implicit Capacitor Stacking for 5G NR Applications

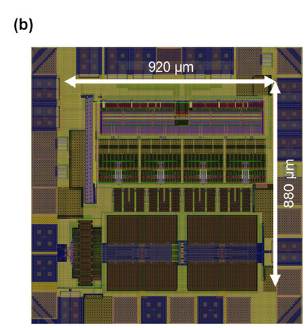
2.07

S. Araei, S. Mohin, N. Reiskarimian

The sub-6GHz spectrum is heavily utilized by 5G New Radio (NR) and traditional cellular applications, calling for versatile widely-tunable receivers. Mixer-first receivers are considered appealing candidates for 5G RXs due to their flexibility and high out-of-band linearity. These structures, however, are vulnerable to harmonic blockers, posing a significant challenge to their design.

In this work, we propose a low-loss fully-passive harmonic rejection mixer incorporating bottom-plate mixing, featuring fewer switches, extended frequency range, and reduced complexity compared to the state-of-the-art HR mixer. Besides eliminating harmonic blockers at the HR mixer output, this design suppresses 3rd/5th harmonic blockers at the antenna interface by >22dB, leading to higher linearity. The proposed HR mixer structure can be incorporated into any passive-mixer-based voltage-mode receiver to enhance its resilience to harmonic blockers and is a promising candidate for 5G NR applications.





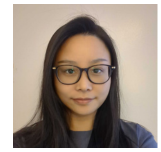
▲ (a) Block diagram of the proposed architecture (b) Chip layout

Highlight: Efficient and Flexible DNN Acceleration with Hierarchical Structured Sparsity

2.08

Y. Wu, P.-A. Tsai, S. Muralidharan, A. Parashar, V. Sze, J. Emer

Sponsorship: MIT AI Hardware Program



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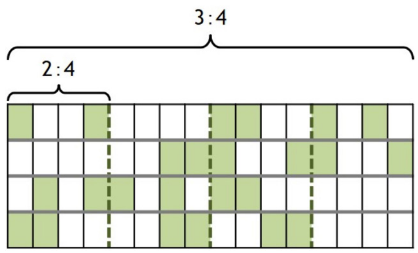
Research Interests:
Energy, Multimedia, Systems, Computer Architecture.

Deep neural networks (DNNs) are widely used in many applications and often involve activations and weights that are either dense or of varying sparsity degrees. Since sparsity can introduce hardware processing savings, an ideal DNN accelerator should efficiently exploit the diverse sparsity characteristics. However, existing works either implement low-cost but inflexible support for structured sparse DNNs with very limited degrees or provide flexible but high-cost support for unstructured sparse DNNs with diverse degrees.

This work addresses the limitations by providing a compromise that supports many degrees of structured sparsity at a low cost. We first introduce hierarchical structured sparsity (HSS), which allows systematic representation of various sparsity degrees. Based on HSS, we co-design a pruning scheme and an accelerator, named Highlight, that enables efficient processing of high accuracy DNNs with different sparsity characteristics. Highlight achieves upto 20x better energy-delay-product (EDP) compared to existing designs.



▲ Example hierarchical structured sparsity with two levels along each row. The inner level has a 2:4 sparsity pattern (i.e., 2 non-zeros in each block of 4), and the outer level has a 3:4 sparsity pattern (i.e., two non-empty blocks in every 4 blocks).

260GHz Transceiver with High-Efficiency Antenna in-Package on 22nm FinFET Process

2.09

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Sponsorship: Intel Corporation

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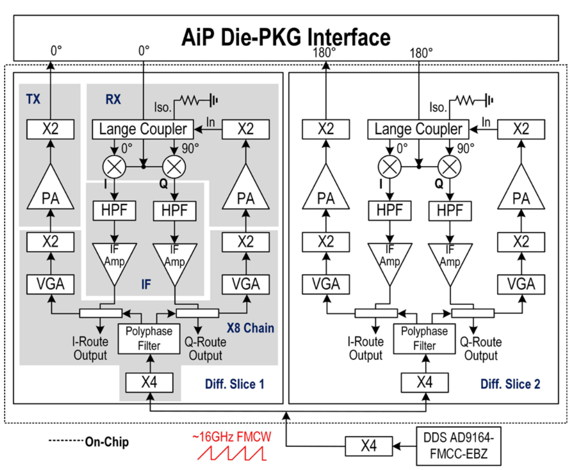
Research Interests:
Communications, Electronic devices, Electronics, Integrated circuits, Optoelectronics, Photonics, Si, Systems, CMOS, Electromagnetics.

CMOS-based on-chip antenna for sub-THz radiation suffers from its inherently low radiation efficiency, due to extremely small thickness of dielectric stack, and lossy silicon substrate. Transistor cut-off frequency (fmax) in nowadays mainstream CMOS processes further introduces significant hurdles for generating high radiated power at sub-THz regime, especially when the operating frequency exceeds 200GHz. This work shows a 260GHz transceiver design with high-efficiency antenna-in-package (AiP) design, based on Intel 22nm FinFET process. Simulation shows the highest radiation efficiency among all other reported CMOS works under the same frequency. An on-chip 260GHz transceiver is designed to pair with the AiP. The whole system shows a simulated wide bandwidth and decent radiated power, which translates to high ranging resolution with long detection range for FMCW radar detection.



◀ 260GHz Transceiver System Diagram.

Energy efficient, low memory accelerator for TinyML applications

2.10

D. Kochar, A. Chandrakasan

Sponsorship: MIT EECS – Advanced Micro Devices Undergraduate Research and Innovation Scholar

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Research Interests:
Artificial Intelligence, Electronics, Energy harvesting devices & systems, Integrated circuits, Machine Learning, Si, Systems.

Deep convolutional neural networks are increasingly being used in speech recognition, vision and signal processing applications, and have achieved great success, but the large memory requirement and computation results in a lot of power consumption. Always-on IoT interfaces are becoming increasingly common in wearable devices with low power being a critical design constraint. Image and audio data sent by IoT devices to the cloud for processing is impractical for energy and privacy concerns, thus, a need for on-chip processing. Achieving sufficient energy efficiency to execute ML workloads on them necessitates specialized hardware with efficient digital circuits.

The objective of the work is to propose a general purpose accelerator for TinyML supporting a wide range of applications. By processing a layer-by-layer computation, the accelerator design uses a large memory to store intermediate data. This data is usually too large to fit on chip, necessitating off-chip memory, which increases area and latency. So, the proposed chip will support fused layer architecture to process multiple CNN layers together by changing how the input data is brought in, while intermediate data is cached.

With the motivation that usage will be in conjunction with an energy harvesting module, the energy available at any given time may not be sufficient to support a full bitwidth computation. Hence, a PE structure that can be broken/joined to support different quantization schemes will be used. Early synthesis results show that such a fused PE which can support 2, 4, 8 bit inputs and weights takes only 2x the area which just a 2 bit input and weight PE does. To reduce power, near threshold voltage design will be implemented for memory for weights and activation cache. Design exploration across various supply voltages and transistor sizing for various SRAM designs show the 8T-SRAM being a strong contender.

This can be used for KWS, noise cancellation, pupil detection, VWW and other such applications.

Architectural Evaluation of Processing-In-Memory Accelerators

2.11

T. Andrulis, J. Emer, V. Sze

Sponsorship: Ericsson, TSMC, MIT AI Hardware Program

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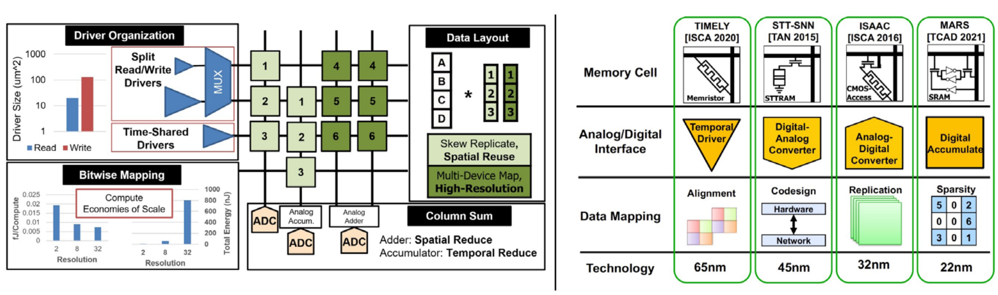
Deep Neural Network (DNN) computation is limited by high data movement costs. Processing-In-Memory (PIM) accelerators are a promising solution as they move compute into memory and reduce expensive data movement. Unfortunately, research has mainly focused on devices (e.g., memristors), circuits (e.g., analog converters), or architecture (e.g., dataflow) in isolation. It is desirable to see how innovation at any level, such as new devices, may change the efficiency and performance of whole accelerators. This would enable fair comparison of innovations and yield insight into the vast number of ways to combine them.

We present a framework that models PIM at an architectural level. With up to 10,000x faster simulation and adaptable PIM device, circuit, and architecture models, our framework enables rapid design space exploration and shows researchers how innovations affect the efficiency and performance of PIM accelerators. This opens opportunities for innovation and exploration in the PIM accelerator design space.



▲ Left: PIM analog crossbar design showing options in drivers/column sum (Circuit) and in data layout/bit mapping (Architecture). Right: Previous works' design choices. The number of combinations is large and needs a rapid framework to explore.

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Research Interests:
Integrated circuits, Systems.

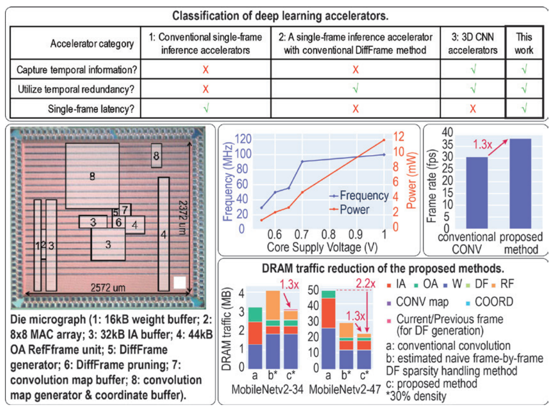
VideoTime3: A 61.3uJ/frame 38FPS Video Understanding Accelerator with Real-Time DiffFrame Temporal Redundancy Reduction and Temporal Modeling

2.12

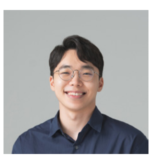
M. Wang, Y. Lin, Z. Zhang, J. Lin, S. Han, A. P. Chandrakasan

Sponsorship: Qualcomm Incorporated

The rise of technologies, such as object tracking for drones, has highlighted the need for accurate and energy-efficient video understanding on the edge. To realize that, deep learning (DL) is widely used for its high accuracy. We classify recent DL accelerators into 3 categories (Fig.) and find that it remains challenging to capture temporal information and utilize temporal redundancy in videos while achieving single-frame latency for real-time applications. To tackle the challenges, we present an algorithm-hardware co-design approach for efficient video understanding on the edge. We propose: 1) RealTimeDiffFrameConvolution achieving 1.3x DRAM access reduction at single-frame latency compared to existing sparsity-handling method; 2) sorter-free architecture for sparse output stationary dataflow; 3) specialized data buffering to remove DRAM traffic overhead for temporal modeling and reduce 55~79% IA DRAM traffic in certain layers. Die photo and measurement results are shown in Fig.



◄ Classification of deep learning accelerators, the die photograph of the proposed accelerator and the measurement results (IA: input activation; OA: output activation; DF: DiffFrame; RF: RefFrame; COORD: coordinate; CONV: convolution.)



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Research Interests:
Communications, Energy harvesting devices & systems, Integrated circuits.

A 1.54mm2 Wake-Up Receiver Based on THz Carrier Wave and Integrated Cryptographic Authentication

2.13

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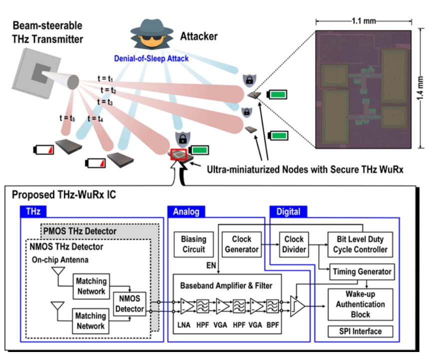
Sponsorship: NSF, Korea Foundation for Advanced Studies (KFAS)

Unobtrusive and mass-deployable wireless nodes are critical components in the next-generation Internet of Things for monitoring environments. Thus, there is a growing interest in mm-sized wake-up receivers (WuRxs) to save the limited energy of those nodes. However, the size of RF WuRxs is limited by the antenna due to the wavelength dependence, which is cm2-size in the GHz range.

This work presents a 1.54mm2 WuRx by pushing the carrier wave to the THz spectrum with on-chip antenna integration achieving the -48dBm sensitivity, 2.88μW power consumption at the 1kbps data rate. Pseudo-differential dual-feed, cold-FET detector pairs are proposed for WuRx optimization, and a low-power authentication block is introduced to prevent Denial-of-Sleep attacks. Several meters of operational range and wireless beam-steering are provided to demonstrate the feasibility of THz connectivity for next-generation IoT. This work demonstrates a low-cost, fully-integrated solution for WuRx miniaturization.



◄ Application scenario of using secure THz WuRx with ultra-miniaturized nodes and the block diagram of the proposed WuRx.

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Research Interests:
Biological devices & systems, Energy, MEMS & NEMS, Molecular & polymeric materials, Nanomaterials, Nanotechnology, Sensors, Systems.

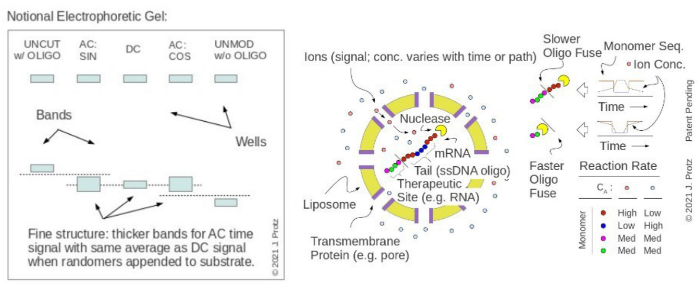
Bionano TERCOM and Silicon MEMS DACS

3.01

J. Protz, A. Lee, A. Jain, B. Vasievich, M. Slowe, T. Labean

Sponsorship: Protz Lab Group, microEngine, LLC, Asteria Propulsion LLC, Ariadna

Many approaches to targeted drug delivery target cell-borne receptors or use external stimuli to drive spatially-localized release. In this work, particles instead estimate their location within the body by correlating the evolution of their sensed environment (e.g. temp., salinity, etc.) against a map they carry, then release on the basis of this estimate; the approach is related to TERCOM, a technique used in air navigation. Current efforts focus on liposome-encapsulated mixtures of oligo-modified RNA and nucleases which produce path-dependent doses of RNA therapeutic while en route to a site. A demo experiment has been designed. The current effort is focused on design of a particle that suppresses dosage near the heart but not in other places. The work builds on past efforts by the PI and his group to develop nanoparticles which record signals in DNA. Progress may enable a new class of engineered pharmaceuticals. The poster will also discuss work by the PI on a Si MEMS DACS.



◄ (right) nuclease with environmental and substrate sensitivity consumes tail faster when environmental path and tail sequence are better correlated; (left) if a mix of random tails is used, electrophoretic gel should exhibit fine structure in bands due to varying correlations between tail sequence and environmental path causing yielded strand length to vary.

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Available from May 2023.

Research Interests: Biological devices & systems, Machine Learning, Medical devices & systems, Microfluidic devices & systems.

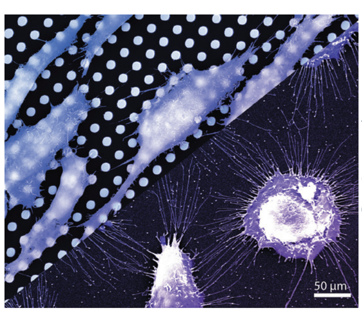
Mediating Cell Adhesion Using Microtextured Polystyrene Surfaces

3.02

C. McCue, A. Atari, S. Parks, M. Tseng, K. K. Varanasi

Sponsorship: Broad SPARC Grant, MIT-Takeda Fellowship

Enzymatic cell detachment strategies for cell culture are popular, but are labor-intensive, can potentially lead to accumulation of genetic mutations, and produce large quantities of waste. Thus, there is a need for surfaces that lower cell adhesion strength while maintaining cell growth to enable enzyme-free cell culture. In this study, we investigated the use of microtexture alone to control cell adhesion. We developed a fast, simple, and inexpensive process for creating microtextured polystyrene surfaces. This fabrication method can transform any design produced with traditional lithography into a PDMS stamp with which we can mold polystyrene, and can be easily scaled for high throughput cell culture as well as create high aspect ratio micron-sized features with high precision and reproducibility. These cell culture surfaces enable decreased cell adhesion strength while maintaining high cell viability and proliferation through a simple reduction in the cell-surface contact area. Using image analysis to quantify cell morphology, we found that surface textures decreased cell area by half and led to much more elongated cell shape compared to flat surfaces. We designed a microfluidic shear force measurement platform to quantify the removal of cells from these surfaces, and showed that significantly more cells were removed from the microtextured surfaces than the flat surfaces, demonstrating that our surfaces lead to decreased cell adhesion.



◄ SEM image of MG63 cancer cells grown on microtextured polystyrene (left), compared with cells grown on flat polystyrene (right), showing how surface texture alone can significantly change cell morphology.

Heart Rate Varies with Mental Workload and Performance in Virtual Reality Flight Tasks

3.03

J. Koerner, H. M. Rao, K. McAlpin, G. Ciccarelli, T. Heldt

Sponsorship: MIT Presidential Fellowship, NSERC Doctoral Scholarship (Application ID PGSD3-547366-2020), U.S. Air Force Research Laboratory, U.S. Air Force Artificial Intelligence Accelerator (Cooperative Agreement Number FA8750-19-2-1000)

Heart rate (HR) has been shown to correlate with cognitive metrics, particularly mental workload, in a variety of settings. In real aviation settings, there is broad consensus that HR is positively correlated with mental workload which makes HR an ideal signal to track as a potential surrogate for mental workload. With the growing use of virtual reality (VR) in different areas of training and education, including pilot training, the question arises if the same relationship between HR and mental workload holds in VR-simulated environments. To this end, this work investigates HR responses derived from electrocardiogram (ECG) recordings in 20 subjects performing flight maneuvers in a VR setting and explores the relationship between HR, mental workload, and flight performance. We find that mean HR increases by 2% ($p < 0.05$) across difficulty levels of the virtual flight scenario, decreases by 5% ($p < 0.01$) across repeated runs of the same difficulty level, and increases by 3% ($p < 0.01$) during the final landing period (with respect to the beginning of the flight). We observe HR to mirror the trend in mental workload and find a statistically significant correlation between HR and flight performance across different flight phases. Although the effect size observed is moderate, the findings are statistically significant and consistent across participants' experience levels. Our findings lend credence to the use of VR simulators for training purposes, and to the idea of titrating training difficulty based on real-time physiological responses in VR-simulated environments. Finally, we show that the ECG-derived HR trends can similarly be derived from photoplethysmography (PPG) signals. Given the existence of PPG sensors approved for cockpit use in real aircraft, our findings have significance beyond the VR setting.

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Research Interests:
Artificial Intelligence, Machine Learning, Medical devices & systems.

High-Throughput Electrokinetic Filter for Media Regeneration

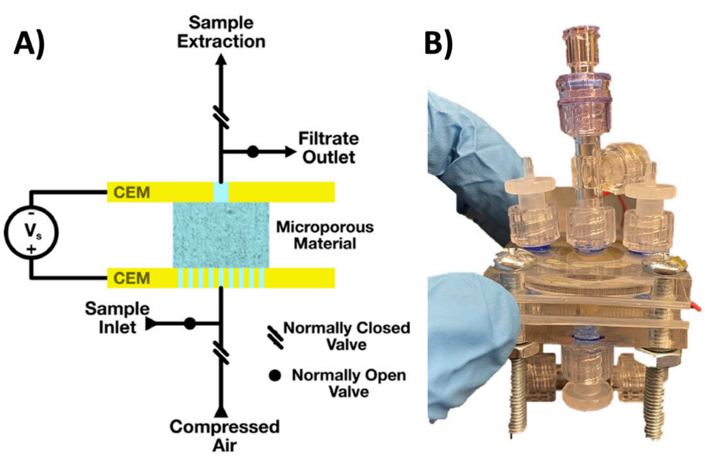
3.04

E. M. Wynne, J. Han

Sponsorship: NIIMBL

Spent CHO cell culture medium contain nutrients and growth factors that are discarded after antibody purification. In a continuous system such as a perfusion culture the harvest stream presents an appealing opportunity for recycling media that is only partially depleted of nutrients. Removing the waste products from the harvest feed and mixing it with fresh media in the feed stream would reduce the amount of raw material needed for culture and therefore reduce cost.

We demonstrate a device that can remove the waste products ammonia and lactate from spent CHO culture media. We explore the operating parameters by examining how filtration conditions such as flowrate and applied voltage bias affect viability of cells cultured with recycled media.



▲ A) Schematic of the of the of the electrokinetic filtration system with cation exchange membrane (CEM) and anion exchange membrane (AEM). B) Photo of the high-throughput filtration device.

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Biological devices & systems, BioMEMS, Medical devices & systems, Microfluidic devices & systems.

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Research Interests:
Biological devices & systems, BioMEMS, Medical devices & systems, MEMS & NEMS, Nanotechnology.

An intracellular antenna for wireless operation in optically opaque environments and 3D biological systems

3.05

R. S. Yang, A. J. Hanson, C. R. Sullivan, B. Joy, Y. Cai, D. C. Bono, D. Sarkar

Sponsorship: MIT Media Lab start-up funding, NIH R00 Pathway to Independence Award R00GM126277-05

An intracellular antenna can enable wireless sensing, modulation, and power transfer for electronic computation within living cells. They could also work in optically opaque environments and in vivo since they communicate using radio frequency waves. However, developing an antenna which can fit inside a cell has remained an unmet challenge since conventional antennas when miniaturized to sub-mm sizes have very low efficiencies due to ohmic losses and operate at very high frequencies harmful for living systems. Here we present the Cell Rover, a 500 μm x 200 μm x 28 μm intracellular antenna fabricated from the magnetostrictive material Metglas, which can overcome the limitations in the miniaturization of conventional antennas and is suitable for operation in 3D biological systems. Cell Rovers can convert incident magnetic fields to acoustic waves by the principle of magnetostriction thereby leading to an operating frequency in the low MHz range which is ideal for living systems. We demonstrate intracellular wireless operation of Cell Rovers in fully opaque, Stage VI, Xenopus Laevis oocytes for which real time sensing with conventional technologies is difficult. Intracellular injection of Cell Rovers is achieved by applying a gradient magnetic field to ensure cell viability following which wireless detection is shown using a gradiometer coil setup. We also demonstrate the possibility of using Cell Rovers for multiplexing applications to communicate with multiple antennas within the same cell or different cells. This technology acts as the basis to integrate wireless sensing, modulation and electronic computation within a living cell and can open up variety of pathways for the fundamental understanding of biology and development of therapeutics.

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Research Interests:
Biological devices & systems, Organic materials, Biomedical Engineering.

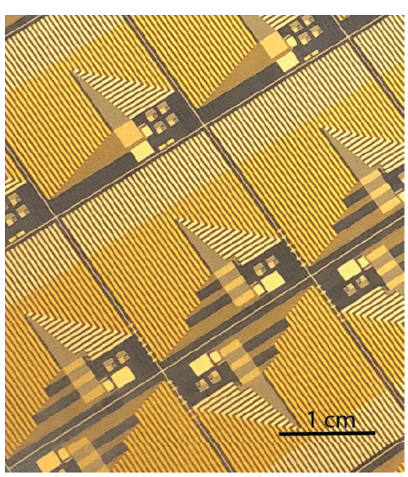
Chamber Design of a Portable Breathalyzer for Disease Diagnosis.

3.06

D. Morales, M. Xue, T. Palacios

Sponsorship: NSF CIQM

Our group has built a graphene-based sensor array than can accurately measure the concentration and type of different chemicals of interest. In this project, we are developing a chamber design that will allow using this sensor as a portable breathalyzer for non-invasive, cheap and fast diagnosis of diseases. Although significant research has been made in this field over the years, none has focused on the optimal chamber design of these devices, which has to optimize contact between sensors and air samples and address issues such as moisture, air velocity control, recirculation and turbulence. Our work studies the airflow properties in different cylindrical chamber models and, with the help of fluid mechanics simulations and experiments with the analysis sensors, attempts to create a reusable in situ breathalyzer design. These results will help develop devices that will be used in clinical trials that, in the future, could be used for diagnosis of Diabetes, Parkinson's and other conditions.



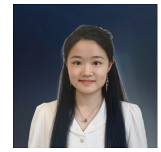
◄ Microscope image of the graphene-based sensor array fabricated on a 4-inch wafer.

A High-Throughput Open-Well Microfluidic Organ-on-Chip System for Blood-Brain Barrier

3.07

F. Xue, U. Lee, W. Liao, J. Voldman

Sponsorship: NIH



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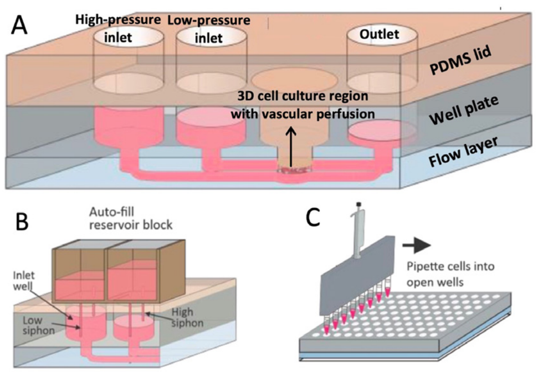
Available from May 2028.

Research Interests:
Microfluidic devices & systems.

Blood-brain barrier (BBB) on-chip constructed by microfluidic technology has assisted researchers in understanding BBB physiology and developing therapies for neurological diseases. However, the existing systems typically account for the biological relevance of BBBs at the expense of robustness, throughput, or ease of operation.

In this work, a BBB on-chip is developed incorporating all four factors above. The system aims to maintain biological sophistication by modeling the architecture of in-vivo BBB and enabling vascular perfusion. The open-well design eliminates bubble-prone tubing operations and improves robustness, and coupling with a standard 96-well plate enables high-throughput operation. A siphon-based design maintains fluid levels at the inlets to ensure gravity-driven flow at a constant perfusion rate. The system can be used to investigate BBB functioning robustly and productively, enabling faster development of therapies for neurological diseases such as Alzheimer's.



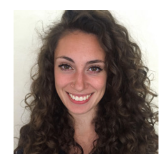
◄ Open-Well Microfluidic Organ-on-Chip System. A) Perfusion culture region. B) Siphon-based autofill reservoir maintains a constant fluid level at the inlets. C) Open-well design allow easy access to fluid and culture region.

A Biocompatible Implanted Microphone for Cochlear Implants

3.09

E. F. Wawrzynek, A. Yeiser, L. Graf, J. Z. Zhang, E. S. Olson, H. H. Nakajima, J. H. Lang

Sponsorship: NIH R01DC016874, Edwin S. Webster Graduate Fellowship



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Available from June 2028.

Research Interests:
Biological devices & systems, BioMEMS, Medical devices & systems, Sensors.

Cochlear implants are a neuroprosthetic that can restore hearing loss to people with damaged inner ears. Currently, cochlear implants rely on an external microphone, but internalizing the entire unit would greatly improve the user's quality of life. An implanted microphone minimizes limitations of wearer activities, takes advantage of the outer and middle ear filtering, and is visibly discrete to avoid social stigma.

We report a bimorph piezoelectric cantilever microphone that can be implanted just below the bottom tip of the malleus. Additionally, we present a custom 3D-printed titanium mounting structure that screws into the posterior ear canal wall and secures our sensor in the middle ear. Our recent research focuses on making our current working device biocompatible without sacrificing performance. We explore both hermetic encapsulation with titanium and non-hermetic encapsulation with Parylene C for isolating our device from the middle ear environment. Furthermore, we investigate viable nonreactive conductive materials for electrode and shielding layers in the cantilever. Through bench testing and cadaveric experimentation, we compare our new device's frequency response, linearity, and EMI sensitivity with that of our previous, non-biocompatible sensor. Furthermore, we present implantation of our sensor and titanium mounting structure during posterior tympanotomy surgery. We demonstrate that our mount provides the cantilever sensor with sufficient stability by measuring mount vibrations with laser doppler vibrometry and by comparing sensor data taken with the new and former mounting systems. By focusing on material choice and structural methods for securing our sensor, we are taking important steps towards a completely implantable microphone for assistive hearing devices.

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Research Interests:
Actuators, Electronic devices, Electronics, Energy, Energy harvesting devices & systems, GaN, Power management.

Field Cancellation for Circuits Encircled by VHF Wireless Power Transfer Coils environments and 3D biological systems

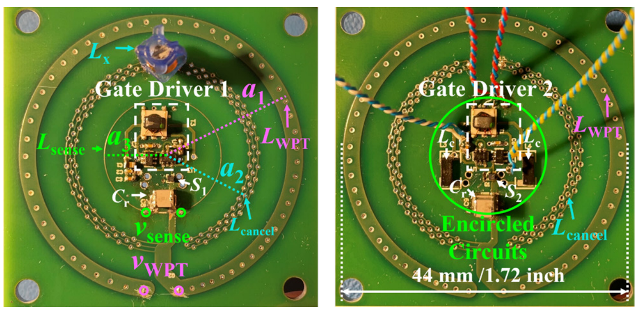
3.10

R. S. Yang, A. J. Hanson, C. R. Sullivan, X. Zan

Sponsorship: MIT Media Lab start-up funding, NIH R00 Pathway to Independence Award R00GM126277-05

Wireless powering technology benefits the miniaturized implantable and wearable medical devices without exit site infection by cutting off the percutaneous wires. Components and circuits encircled by wireless power transfer coils for implantable and wearable medical devices allow miniaturization but require field cancellation for components and circuits that are sensitive to the magnetic field. Very high frequency operation reduces the volume and number of components, which makes encirclement within WPT coils easier, but easily induces voltage and current.

A field cancellation method is investigated to minimize the magnetic field for the encircled circuits in WPT coils using a two-coil structure toward the best cancellation performance, practical construction, and minimum cost at VHF operation. The WPT and canceling coils are driven together by a single current-mode class D power converter with opposite-phase currents to optimize the field cancellation within the coils. Using this cancellation method, the magnetic field for the encircled circuits was reduced by 99% in hardware compared to that without cancellation. There is also a tradeoff between field cancellation performance and power transmission performance.



◄ Miniaturized hardware with the field cancellation method.

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Research Interests:
Artificial Intelligence, Biological devices & systems, BioMEMS, Electronics, Machine Learning, Medical devices & systems, Microfluidic devices & systems, Optoelectronics, Photonics.

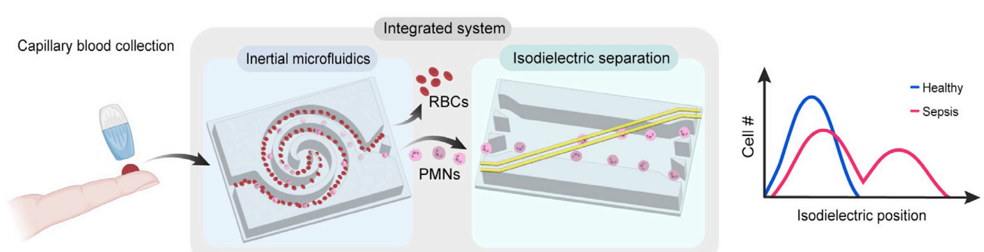
Monitoring Pro-resolving Leukocyte Responses in Peripheral Blood Predicts Clinical Severity During Sepsis

3.11

R. Rodriguez-Moncayo, J.-A. Preuss, J. Bahnemann, J. Voldman

Sponsorship: Institute of Physics, University of Augsburg, NIH

In the United States, sepsis affects 1.7 million adults yearly, generating a cost of $14 billion and contributing to over 250,000 deaths, making it a leading cause of death. Sepsis is a dysregulated response of immune cells to infection, resulting in systemic inflammation that induces organ injury. A better understating of the pro-resolving mechanisms that must be engaged by immune cells during the resolution of sepsis is necessary to propose new therapeutic targets. We propose a longitudinal analysis to monitor sepsis and its resolution, by probing the activation of immune cells recovered from microliter quantities of blood. For this, we have developed an integrated microfluidic system which isolates and analyzes the activation state of immune cells via inertial microfluidics and isodielectric separation, respectively. PMNs sorted via their isodielectric position, a correlate of activation state, could be collected and further analyzed to identify the intracellular signaling networks that become engaged during the resolution phase. This information could lead to the identification of therapeutical targets, potentially increasing patient survival.



▲ Monitoring cell activation during sepsis and its resolution using an integrated microfluidic approach.

High-efficiency Icrofluidic Cell Pairing and Fusion for Cell-based Cancer Vaccine Development

3.12

F. Zheng, R. Rodriguez-Moncayo, U. Lee, J. Voldman

Sponsorship: NIH

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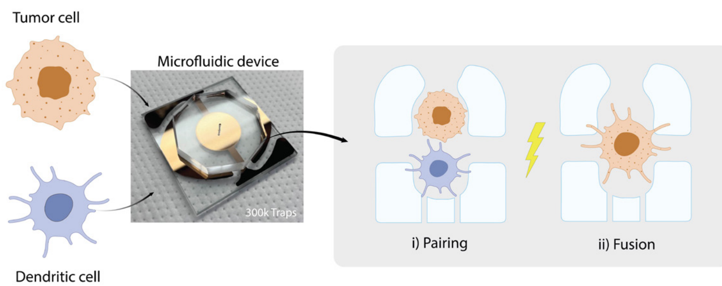
Visiting affiliate supervised by Joel Voldman.

Research Interests:
Biological devices & systems, BioMEMS, Medical devices & systems, MEMS & NEMS, Microfluidic devices & systems, Molecular & polymeric materials, Nanomaterials, Nanotechnology.

Some cancers are notorious for poor prognosis. Personalized immunotherapies are promising due to their high specificity, long-lasting protection, and low toxicity. Among these therapies are cell-based vaccines where the patient's own tumor and dendritic cells (DCs) are paired and fused to generate hybrid cells, capable of presenting tumor antigens. Conventional methods to generate hybrid cells show low efficiency mainly due to the lack of control during cell pairing. Here, we propose a microfluidic platform for the highly efficient pairing and electrofusion of tumor and DCs. We use microfluidics due to high control of fluids, compatibility with single cells, and low sample consumption. Our device is made of polydimethylsiloxane and contains 300,000 microtraps of 25 μm high and 70 μm wide, where cells are sequentially loaded and isolated. To characterize and optimize our device, we employ model cell lines which resemble immune and cancer cells. Our approach should lead to a controlled and robust generation of DC-tumor hybrids, contributing to clinical translation of highly specific cell-based immunotherapies and significantly impacting cancer treatment.



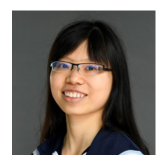
▲ Highly efficient microfluidic cell pairing and fusion for cancer vaccine development.

Accelerating the optimization of Vertical Flow Assay Performance guided by a Rational Systematic Model-based Approach

3.13

D. M. Y. Tay, S. Kim, Y. Hao, E. H. Yee, H. Jia, J. Voldman, H. D. Sikes

Sponsorship: HKUST-MIT Research Alliance Consortium, Singapore's National Research Foundation, MIT Summer Research Program (MSRP)



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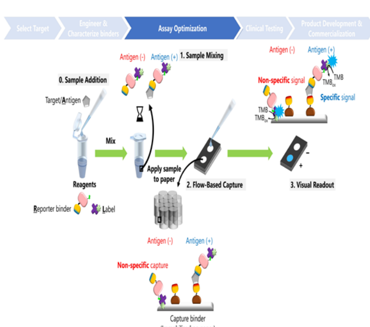
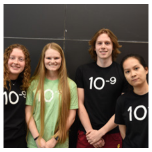
Research Interests:
2D materials, Artificial Intelligence, Biological devices & systems, BioMEMS, Machine Learning, Medical devices & systems, MEMS & NEMS, Microfluidic devices & systems, Nanomaterials, Nanotechnology, Sensors.

Rapid diagnostic tests (RDTs) have shown to be instrumental in healthcare and disease control. However, the laborious and empirical, yet necessary, development and optimization process for the attainment of clinically relevant sensitivity remains inefficient. While various studies have sought to model paper-based RDTs, they do not encompass all possible operation regimes. It is also unclear how the model predictions may be utilized for optimizing assay performance. Here, we propose a streamlined and simplified model-based framework for the acceleration of assay optimization, which relies on minimal experimental data. These models are based on physically rational formulations accounting for relevant physical phenomena such as mixing and diffusion. We show that our models can recapitulate experimental data and estimate of several pertinent assay performance metrics such as limit-of-detection, sensitivity, signal-to-noise ratio and difference. We believe that our proposed workflow would be a valuable addition to the toolset of any assay developer, regardless of the amount of resources they have in their arsenal, and aid assay optimization at any stage in their assay development process.



◄ Schematic of proposed assay optimization workflow.



Design and Fabrication of a Flexible Pulse Oximeter

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Sponsorship: MIT EECS, 6.2540 Class

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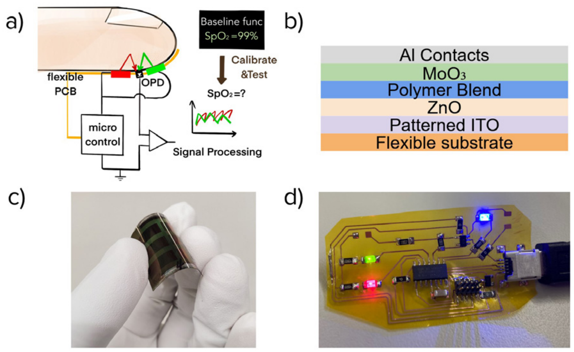
3.14

Pulse oximetry is a commonly used technique for monitoring oxygen level in humans. Conventionally, they are often bulky, hence, less convenient for use in applications requiring continuous monitoring. Thus, alternative designs enabling oximeters in a wearable form-factor are desired. To this end, we propose the design of a flexible oximeter composed of a flexible organic photodetector (OPD) integrated with a flexible printed circuit board (PCB) carrying on-board a low-power microcontroller running a real-time pulse detection algorithm. A schematic of the oximeter design is shown in Figure 1a. The device stack of the flexible photodetector is shown in Figure 1b and an example of the fabricated device is included in Figure 1c. The flexible PCB, shown in Figure 1d, is fabricated through lithographic etching of copper-coated polyimide thin-film onto which the oximeter components are soldered. Once integrated, this platform provides a basis for a fully-flexible pulse oximeter.



▲ a) Overall schematic of the pulse oximeter, b) Architecture of the flexible OPD, c) Photograph of the fabricated flexible OPD, d) Photograph of the fabricated PCB with polyimide substrate

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Research Interests:
2D materials, Biological devices & systems, BioMEMS, Energy, Energy harvesting devices & systems, Microfluidic devices & systems, Nanomanufacturing, Nanotechnology, Thermal structures, devices & systems.

Exploring the Limits of Bubble Capture and Transport through Porous Aerophilic Membranes

4.01

B. J. C. Vandereydt, S. Nath, T. Joseph, K. K. Varanasi
Sponsorship: NTT Research Inc, NSF Eager, NSF GRFP

Hydrophobic membranes are a common tool to capture unwanted bubbles in applications ranging from microfluidics, to gas evolving electrochemical systems, to bioreactors for foam prevention. In these, rapid bubble capture on the order of milliseconds is required as longer times will lead to bottlenecks. In this work we seek out the mechanisms behind capillary driven transport of a bubble through a hydrophobic membrane. For this, we fabricate super-hydrophobic nano-structured silicon membranes with a DRIE etching technique with variable hole diameter and spacing. Through altering physical parameters of the membrane, we have identified three different limiting regimes of bubble capture through a membrane. With the use of scaling laws, we can predict the transition between regimes. From thisa predictive non-dimensional phase-map is build that can be used to design new membranes. At the high-end, bubble capture times under 1ms have been recorded for millimetric bubbles. This work elucidates the limiting factors behind bubble transport through a membrane, and its results can be translated to applications where bubble capture is required.

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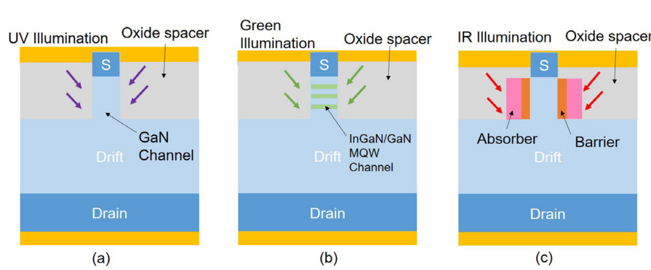
Research Interests:
2D materials, Electronic devices, Electronics, Energy harvesting devices & systems, GaN, III-Vs, Integrated circuits, Light-emitting diodes, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Power management.

Optically Controlled Vertical GaN Power finFETs

4.02

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

In recent years, the boost in consumer electronics, automotives 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. Although optically triggered silicon devices have already been developed, there are no demonstrations on optically controlled GaN power transistors. In this project, we are evaluating the performance of optically-controlled GaN transistors as shown in Figure 1. Initial simulations have shown optical gain of >10^3 through the electrostatic control of fin channel.



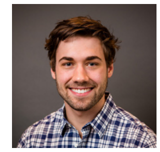
◂ Approaches for optically triggered devices (a) Directly-triggered UV finFET with GaN channel (b) Directly-triggered blue/green finFET with embedded InGaN/GaN MQWs (c) Absorber-coupled finFET.

Vertical GaN Superjunction Transistors

4.03

J. Perozek, T. Palacios

Sponsorship: ARPA-E 2021 OPEN Project



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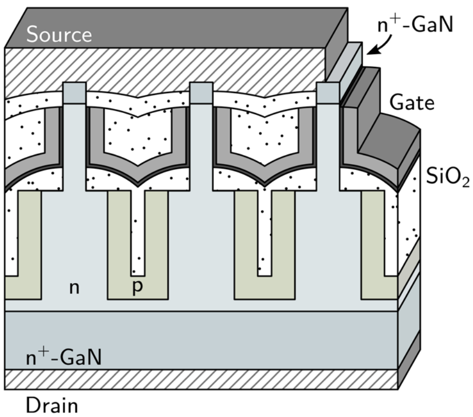
Research Interests:
Electronic devices, Electronics, Energy, GaN, III-Vs, Nanotechnology.

Increasing sustainable energy practices have spurred the need for next generation power conversion systems. At their core, these systems, which are essential for solar farms, data centers, and electric vehicles, require small, fast, and affordable power transistors. While gallium nitride (GaN) as a material is uniquely suited for these applications, existing transistors are far from their theoretical limits. The inability to optimize the electric fields within the device has prevented commercial transistors from achieving their promised performance.

In this work, we aim to use our expertise in fabricating vertical GaN FinFETs to surpass the unipolar limit and create the first GaN superjunction transistors. These devices use alternating n- and p-type regions to minimize on-resistance and optimize the electric field profile within the transistor to reach GaN's theoretical limits. Such devices could outperform existing tech by 50-100× and significantly improve energy conversion efficiency.



◄ Schematic of a vertical GaN superjunction transistor.

Design and Optimization of an Inverter for a One-Megawatt Ultra-Light Motor Drive

4.04

M. M. Qasim, D. M. Otten, Z. S. Spakovszky, J. H. Lang, J. L. Kirtley Jr., D. J. Perreault

Sponsorship: Mitsubishi Heavy Industries (MHI)

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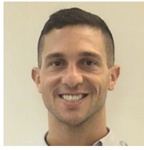
Research Interests:
Electronic devices, Electronics, Energy, Energy harvesting devices & systems, Integrated circuits.

The world's increasing commitment towards environment-friendly electric transportation including electric vehicles, aircrafts, trains and electric ships motivate the development of high-power, light-weight and efficient motor drives (including the electric machine and power electronic converter subsystems). However, the electric machine is traditionally designed and optimized without necessarily the knowledge of the power electronics that would drive it, and vice-versa. Moreover, the thermal management for each of the two subsystem is often designed separately. All these subsystems (the power electronics, electric machine, and their thermal management) however, are inherently coupled and can affect the overall system performance. As a result, the decoupled design approach usually results in less than optimum performance of the overall system, including weight and efficiency.

Our research in collaboration with the Gas Turbine Lab (GTL) at MIT aims to develop a 1-MW high-speed, high-specific-power-density motor drive demonstrator for aircraft applications. The three subsystems (electric machine, power electronics and thermal management system) are co-designed and co-optimized for weight and efficiency benefits of the overall system. Unlike the traditional power conversion concept which consists of a single unit of 1-MW inverter driving a three-phase electric motor, we propose a distributed power conversion architecture that is closely coupled with the electric motor for weight benefits of the overall system. The proposed 1-MW inverter consists of ten 100-kW inverter sets distributed around the periphery of the machine to drive ten separate sets of three-phase windings. Each inverter set consists of three single-phase full-bridge inverters each of which drives a phase winding. The co-optimized motor drive has significant benefits in overall specific power exceeding the NASA's performance target for megawatt-class electric propulsion.



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Research Interests:
GaN.

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

4.05

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

GaN HEMT technology is a promising candidate for next-generation power devices. Since power management applications involve operating the transistors under repeated switching, reliability and robustness is a significant concern. Under switching operation, critical parameters such as the dynamic on resistance, $R_{DS,ON}$, and the turn-on gate threshold voltage, V_T, are subject to the influence of various trapping effects. When operating under hard-switching conditions, the device is subjected to high current and high voltage levels simultaneously. This operation mode has a significant impact on device parameters drifts which present a limitation on large scale application of GaN power devices.

The aim of this work is to devise techniques to continuously monitor V_T and $R_{DS,ON}$ under hard-switching operation, and to investigate the role of transition on parameters drift. To this end, we have constructed a unique experimental setup capable on repeating the Double-Pulse Testing Technique multiple times and measure device parameters in-situ. The experimental results show the evolution of V_T and $R_{DS,ON}$ under hard-switching conditions and various stress conditions. V_T and $R_{DS,ON}$ drift markedly and a correlation between V_T and $R_{DS,ON}$ degradation was observed. Study of the impact of hard-switching on the evolution of device parameters is still under investigation. This work will help identify the underlying mechanism that may be responsible for both drift and contribute to the understanding of failure modes in GaN devices.

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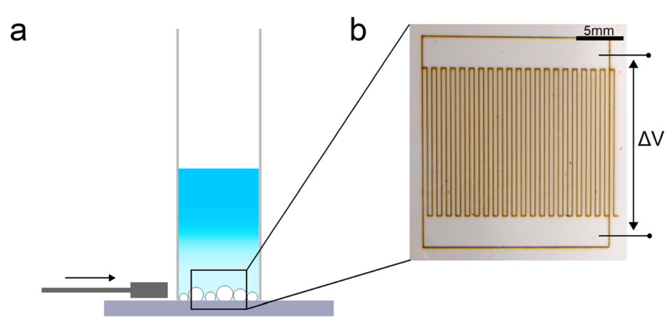
Research Interests:
2D materials, Batteries, Biological devices & systems, BioMEMS, Energy, Energy harvesting devices & systems, MEMS & NEMS, Microfluidic devices & systems, Molecular & polymeric materials, Nanomanufacturing, Nanomaterials, Nanotechnology.

Deicing with in situ Electrolysis

4.06

H. L. Girard, S. Nath, H. E. D. Kang, S. B. Subramanyam, Y. Shao-Horn, K. K. Varanasi
Sponsorship: Semiconductor Research Corporation, MIT Quest

Ice accretion is ubiquitous and destructive: be it geophysical structures or exposed mechanical structures as car windshields, powerlines, wind turbines, roofs, and aircrafts, the icing problem is everywhere and comprises a multibillion-dollar problem in the United States alone. Traditional methods for deicing rely on mechanical scrubbing, heating, or chemical melting, and are crude, inefficient, and even environmentally toxic. Here we propose a fundamentally different approach to the classical problem of deicing using in situ water electrolysis. We show with experiments how a progressing ice front can trap the electrolytically generated bubbles at the interface. Such trapped bubbles can be used to significantly diminish the energy required to fracture ice. We discuss how the proposed mechanism constitutes a self-starting, self-limiting means to reduce ice adhesion– a feature hitherto non-existent.



▲ (a) Simplified schematic of the ice adhesion measurement setup consisting of the electrolysis substrate, a cuvette containing water and a force gauge. (b) Representative image of the electrolysis substrate consisting of sputtered Pt interdigitated electrodes.

3D-Printed Langmuir Probes for CubeSats

4.07

Z. Bigelow, L. F. Velásquez-García

Sponsorship: MIT Portugal, NewSat Flagship Project

The ionosphere is a portion of the atmosphere consisting entirely of plasma and is closely related to global warming. Characterizing this plasma is therefore advantageous for learning more about solutions for global warming. CubeSats are compact, lightweight satellites designed to carry out specific space missions (e.g., characterizing the ionosphere). Their small size makes CubeSats an economic and environmentally friendly choice. Therefore, it is important to minimize the size and weight of the devices onboard a CubeSat. Additionally, additive manufacturing of the devices allows for rapid prototyping of complex objects, even in space. In this project we are exploring the development of the first additively manufactured Langmuir probes for CubeSat plasma diagnostics, with emphasis on miniaturization.

Preliminary tests have been conducted on a single Langmuir probe and have utilized a probe electrode with a 0.5 mm by 0.5 mm cross-section, additively manufactured in stainless steel via binder jetting, with housing that is 3D-printed in a glass-ceramic material via vat photopolymerization. The ultimate goal is to demonstrate a fully 3D-printed plasma sensor. The 3D-printed single Langmuir probe presented here was used to characterize a laboratory helicon plasma, estimating an electron temperature (9.5 eV), plasma density (2.1×10^{13} m^{-3}), plasma potential (33.8 V), and floating potential (0.4 V)— overall in agreement with the estimates from a control probe. Improvements to the device include using low-power, compact circuitry, exploring different electrode materials, and incorporating different probe geometries and configurations.

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High-power AlGaN finFET for mm-Wave Applications

4.08

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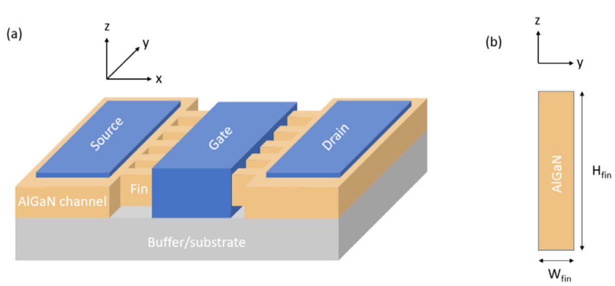
Sponsorship: U.S. Army Research Office (ARO)

High frequency electronics is becoming increasingly important for today's commercial, military and space communication needs. To enable the mm-Wave 5G network, power amplifiers need to provide high power density, gain, efficiency and linearity; but the performance of state-of-the-art GaN HEMTs is limited for frequencies > 30 GHz. AlGaN is an UBWG material that has 3-5 times higher JFOM compared to GaN due to its much higher breakdown electric field (> 8 MV/cm). Therefore, AlGaN devices have the potential to surpass GaN HEMTs and achieve a much higher power density at frequencies > 90 GHz as well as better linearity and efficiency at lower frequencies.

In this project, we propose to leverage the superior material properties of high-Al content AlGaN to fabricate a finFET with fins of aspect-ratio () > 20:1. The tall fin structure increases the effective width of the channel and hence would lead to a higher current density and power density, thus enabling mm-Wave applications.



▲ (a) Schematic of the proposed AlGaN finFET. (b) Cross-section of the fin, target > 2 µm.

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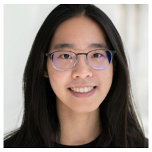
Research Interests:
2D materials, Displays, Electronics, Field-Emitter devices, GaN, III-Vs, Light-emitting diodes, Nanotechnology.



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Research Interests:
Energy, Power electronics, Power magnetics.

Using Permanent Magnets to Improve Inductor Capabilities

4.09

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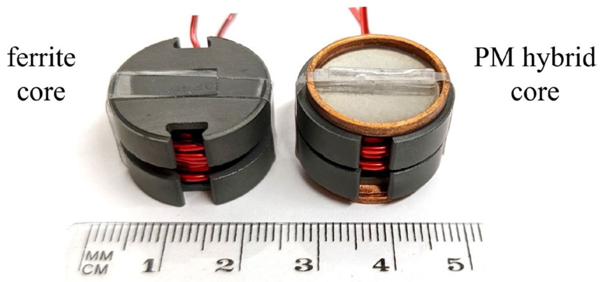
Sponsorship: pSemi, NSF Graduate Research Fellowship (Grant No. 1122374), E.E. Landsman (1958) Fellowship

Power electronics impact the performance, size, and cost of many applications, such as transportation and renewable energy, but they are limited by large and lossy inductors. In many cases, inductor performance is constrained by the maximum magnetic flux density that its core material can carry, known as the saturation flux density.

To improve inductor performance in these cases, we've developed an inductor design that incorporates a permanent magnet (PM) to boost the core material's effective saturation flux density. This design, called a PM hybrid core inductor, can greatly improve loss or energy storage density compared to a conventional inductor with a pure ferrite core. A proof-of-concept prototype of this design, for example, achieves half the dc resistance of a ferrite inductor at the same energy storage. The PM hybrid core inductor design thus may help power electronics achieve greater power density and higher efficiencies.



◄ Picture of a conventional ferrite core inductor and the PM hybrid core prototype.

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Research Interests:
Robotics, sensors, systems.

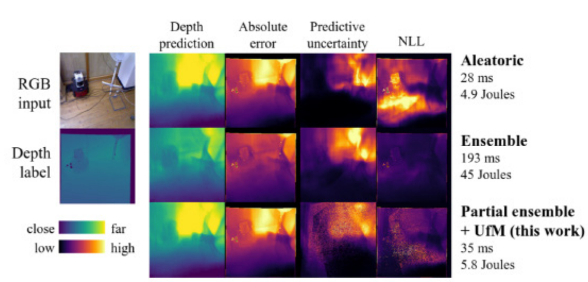
Data Centers on Wheels: Emissions from Computing Onboard Autonomous Vehicles

4.10

S. Sudhakar, V. Sze, S. Karaman

Sponsorship: NSF Cyber-Physical Systems program grant no. 1837212, NSF Real- Time Machine Learning program grant no. 1937501, MIT-Accenture Fellowship

While much attention has been paid to data centers' greenhouse gas emissions, less attention has been paid to autonomous vehicles' (AVs) potential emissions. We introduce a framework to model the emissions from computing onboard a global fleet of AVs and show that the emissions have the potential to be comparable to that of all data centers today. For example, assuming each AV drives one hour a day, the 2020 global average carbon intensity, and a global fleet size with one billion AVs which is less the number of cars on the road today, an average computer power of 0.84 kW on each AV yields emissions equal to emissions of all data centers. Based on current trends, a widespread AV adoption scenario where approximately 95% of all vehicles are autonomous requires computer power to be less than 1.2 kW for emissions from computing on AVs to stay under emissions from data centers in 2018 in 90% of modeled scenarios. In a scenario with high adoption of AVs, business-as-usual decarbonization, and workloads doubling every three years, hardware efficiency must double every 1.1 years for emissions in 2050 to equal data center emissions which is faster than the current rate. We discuss avenues of future research unique to AVs to analyze and potentially reduce the carbon footprint of AVs.



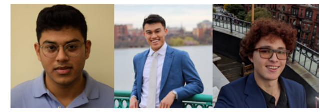
◄ Uncertainty estimation comparison for an aleatoric network, ensemble, and UfM applied to ensembles on an out-of-distribution example from the TUM RGBD dataset. Lower NLL indicates better uncertainty quality.

Low-Energy Robotic Platforms as a Testbed for Resource-Constrained Algorithms

4.11

X. Bell, R. Chowdhury, A. Rice. S. Sudhakar, S. Karaman, V. Sze

Sponsorship: UROP Office, NSF RTML



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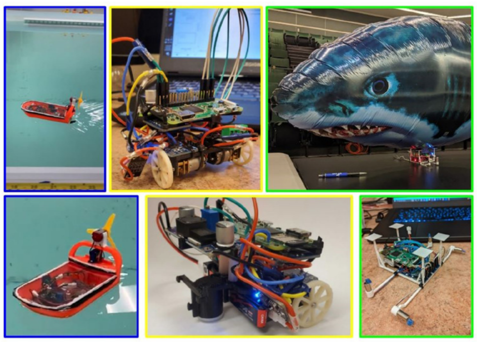
For low-energy robots, the energy consumed by the computing hardware becomes comparable to the energy consumed by the actuators. For these applications, it may sometimes be advantageous to accept a longer path in return for spending less energy on computing, as proposed in the low-power motion-planning algorithm CEIMP [1]. The purpose of our research is to develop three miniature efficient water, ground, and air robotic platforms (boat, car, blimp) with an actuation power to speed ratio of 1W:1m/s to demonstrate the impact of CEIMP. The first iterations of each design for the boat, blimp, and car are currently 6:1, 3:1, and 1:1 respectively for actuation power to speed ratio. The reproducible designs feature lightweight 3D printed structures, power-monitoring sensors, and teleoperation control. In development is a custom PCB, control system, and motion capture integration, enabling our group to begin rigorous testing of CEIMP and potentially other resource-constrained algorithms.



▲ (left, blue) Boat platform running a teleoperated test in the MIT Sea Grant Teaching Tank, (middle, yellow) first iteration of the car platform, and (right, green) blimp platform with and without attached helium balloon.

High-frequency High-power High-Q Cored Inductor Design

4.12

M. V. Joisher, R. S. Bayliss, R. S. Yang, D. J. Perreault

Sponsorship: MKS instruments

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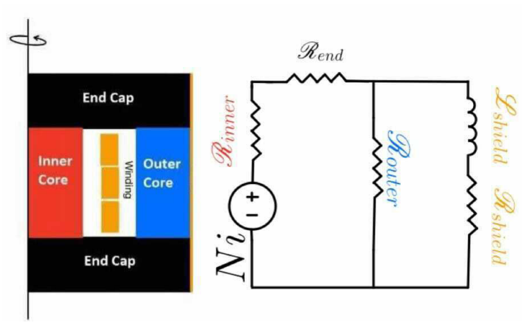
Research Interests:
Batteries, Electronics, Energy, Power management, Power electronics and magnetics.

The performance of a high-frequency circuit is strongly influenced by the performance of the inductor. Air-core inductors with a Q ~ 200-300 are conventionally used and are usually the major contributor to the overall system's loss and size. With the recent advancements in high-performance, high-frequency magnetic materials, there has been some work around leveraging these magnetic materials at HF and replacing lossy air-core inductors with high Q-core inductors. This work proposes a high Q (~1500) core inductor that leverages HF high-performance magnetic material, core geometry, and quasi-distributed gaps to achieve a self-shielded inductor that doesn't emit any flux outside its physical volume and can be placed with other magnetic components without inducing EMI loss. High Q inductors can help improve the performance of the circuit but can still induce electromagnetic interference and loss in surrounding components and thus limit the miniaturization of the overall system.



▲ Polar view of the proposed inductor and equivalent circuit model

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Research Interests:
Artificial Intelligence, Energy, Machine Learning, Nanomaterials.

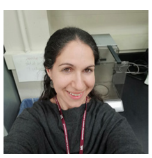
Sub-micron Defect-free and Freestanding Microporous Poly(Arylene Ether) Thin Films for Membrane-based Gas Separations

5.01

J. Y. Yeo, G. Sheng, F. M. Benedetti, D. Syar, T. M. Swager, Z. P. Smith

Sponsorship: ENI and Office of Naval Research – Young Investigator Program (ONR-YIP)

Membrane-based gas separations are viewed as a critical component to accessing low-energy feedstocks and decarbonizinge the chemical industry. However, it is exceedingly challenging to synthesize membrane materials that are high performing, scalable, and processable especially at the nanometer scale. It requires the polymer to have a high molecular weight while still being soluble in organic solvents. As a class of materials, microporous organic polymers (MOPs) have been attracting significant attention for membrane-based gas separations due to their high gas permeability as compared to current commercial polymers. For this project, we present the rational design and synthesis of a new class of linear microporous poly(arylene ether)s (PAEs) via Pd-catalyzed C-O polymerization reactions. The scaffold of these new microporous polymers consists of rigid three-dimensional triptycene and highly stereocontorted spirobifluorene, which endow these polymers with large internal free volume as well as high porosity with angstrom-sized pores. Unlike classic polymers of intrinsic microporosity (PIMs), this robust methodology for the synthesis of poly(arylene ether)s allows for the facile incorporation of functionalities and branched linkers for control of permeation and mechanical properties. This allowed for the fabrication of a submicron defect-free film with permeance-selectivity property sets that are comparable to high-performance ultrathin polymer membranes reported in the literature. The structural tunability, high physical stability, and ease-of-processing suggest that this new platform of microporous polymers provide generalizable design strategies to address outstanding separation challenges for gas separation membranes.



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Research Interests:
Actuators, Electronic devices, Energy, Energy harvesting devices & systems, MEMS & NEMS, Optoelectronics, Organic materials, Photovoltaics.

Vapor Transport Co-Deposition of Perovskite Photovoltaics

5.02

T. K. Zhitomirsky, E. L. Wassweiler, H. L. Tuller, V. Bulović

Sponsorship: U.S. Department of Energy

Halide perovskites have demonstrated remarkably high solar to electrical energy conversion efficiencies and are therefore of great interest for rapid commercialization. Popular solution-based fabrication routes do not lend themselves to rapid scale-up as required. Vapor Transport Deposition (VTD) is beginning to be considered as a readily scalable, low-cost technique alternative method for perovskites production. Vapor-based processes promise to overcome many challenges imposed by solution-based techniques. 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. However, being a newly developing technique, we still need to prove its viability in producing high-quality perovskite films.

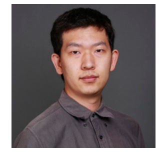
We are currently working with a custom-made VTD system, focused on optimization of co-deposition of lead iodide and methylammonium iodide with the aid of carrier gases. We report our progress in investigating the influence of deposition rate, chamber pressure and post-deposition treatments on the morphology and stoichiometry of the forming perovskite film. We found that there is an inverse relation between chamber pressure and deposition rate, hence deposition of a 500nm active layer required for a solar cell should take no more than 30 minutes, for pressures below 1 torr. We also learned the importance of post-deposition treatments in forming the perovskite phase. These findings can serve us in fabricating solar cells utilizing this new technique.

Distal-contact Catalysis for the Growth of High-purity Semiconducting Carbon Nanotubes

5.03

J. Wang, X. Zheng, G. Pitner, H. Wang, J. Kong

Sponsorship: TSMC



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Research Interests:
2D materials, Electronic devices, Nanomanufacturing, Nanomaterials, Nanotechnology, Carbon nanotube.

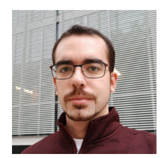
With the development of carbon nanotube (CNT) based electronics, efficient growth of both high-quality and high-purity semiconducting carbon nanotube (s-CNT) arrays has become one of the most important challenges in the carbon nanotube community. To realize the projected speed, efficiency, and scalability of carbon nanotube (CNT) based electronics, the key fundamental challenge is the growth of horizontally-aligned arrays of defect-free SWCNT with a semiconducting purity >99.99%. Until recently, most of the selective SWCNT synthesis methods utilized either the native free energy or native stability difference between the growth of semiconducting CNTs (s-CNTs) and metallic CNTs (m-CNTs). However, such native energy separation is too small to sufficiently suppress the random thermal fluctuation at the 800-900°C growth temperature and fails to deliver semiconducting carbon nanotubes with required >99.99% s-CNT purity. Here we report an approach to open a larger gap in the free energy between m-CNT and s-CNT during both epitaxial growth and chirality change by distally contacting catalyst of CNTs with low work-function electrodes such as Hafnium Carbide or Titanium Carbide. First, the remarkable difference of quantum capacitance between m-CNT and s-CNT separates the CNT free energy plot of CNTs into two branches. Second, when in contact with low work-function electrodes CNTs and tipped catalysts will be negatively charged (n-doped) due to the electrode work-function, which causes an increase in free energy gap between m-CNTs and s-CNT and a reduction of the twisting barrier from m-CNT to s-CNT. Third, the large aspect ratio of CNTs enables a strong local electric field generated by the charge stored at the CNT tip to contribute a prominent electrostatic effect that greatly affects the total free energy change. As a result, stable twisting of horizontally aligned CNTs from initially mixed m-CNT and s-CNT chiralities to s- CNT chiralities is achieved by applying a weak perturbation (10V/mm-alternating electric field). These results validate that a lower work-function contact does result in a higher selectivity towards s-CNTs at a reduced applied electric field. Our observations also open a possibility to select the catalytic pathway through the contact engineering and will pave the way for practical applications of CNT electronics.

Monolithically 3D-Printed Bi-Material Compact Solenoids

5.04

J. Cañada L. F. Velásquez-García

Sponsorship: Empiriko Corporation. The project that gave rise to these results received the support of a fellowship from "la Caixa" Foundation (ID 100010434).



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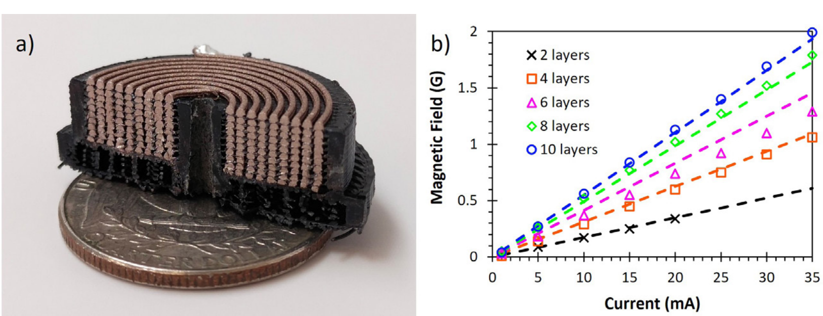
Inductors are ubiquitous in power conversion, actuation, and sensing systems. Their manufacture traditionally implies the winding of wires around a core, although other IC-compatible fabrication techniques have also been demonstrated. Nonetheless, semiconductor microfabrication has limited capability to create three-dimensional objects.

This work reports the design, fabrication, and characterization of the first monolithically 3D-printed, three-dimensional inductors for use in compact systems. The novel air-core, 3D-printed inductors are made via extrusion using PLA-based materials and can generate Gauss-level magnetic fields while drawing tens-of-mA currents. The work is of great interest for fast and inexpensive fabrication of compact sensors, actuators, and power conversion systems, and for integration of electronics with MEMS devices of intricate geometries.



▲ (a) Close-up view of a 10-layer 3D-printed inductor cut in half and (b) magnetic field measurements (markers) and estimates (dashed lines) (J. Cañada and L. F. Velásquez-García, "Fully 3D-Printed Solenoids for Compact Systems", PowerMEMS, 2022).

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Research Interests:
Artificial Intelligence, Integrated circuits, Machine Learning, Sensors.

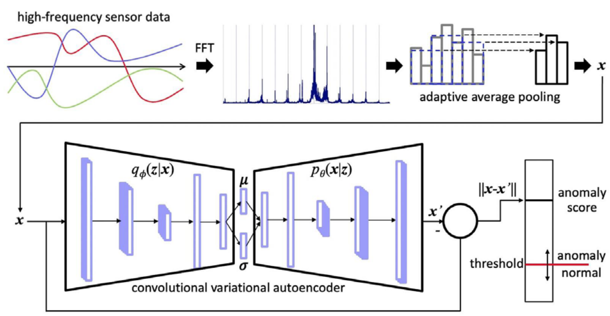
Unsupervised Multivariate Time Series Anomaly Detection for High-Frequency Data

5.05

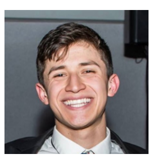
C.-Y. Lai, F.-K. Sun, D. S. Boning, J. H. Lang

Sponsorship: MIT Frederick R. (1953) and Barbara Cronin Fellowship

Detecting anomalies in times series sensor data can prevent potential accidents and economic losses, and thus anomaly detection is highly desirable in a wide variety of industrial applications. However, most studies focus on anomaly detection for low-frequency data (sample rate <100Hz), while others considering high-frequency data are limited to specific applications. Here, we propose a general unsupervised learning framework for anomaly detection on multivariate high-frequency time series. We slice, down-sample, apply the Fourier transform, take the logarithm of the magnitude, apply adaptive average pooling on this result, and smooth data from multivariate equipment sensor streams. We train a convolutional variational autoencoder on this preprocessed data, thereby characterizing "nominal" behavior for that equipment. For anomaly detection on new data (similarly preprocessed) from the equipment during continued operation, we use the reconstruction loss as the anomaly score. On several public datasets and a self-generated high-frequency dataset, our model outperforms most state-of-the-art models specialized for low-frequency data. This extends the applicability of time series anomaly detection towards a more general and diverse body of sensor data.



◀ Proposed preprocessing and learning scheme for unsupervised anomaly detection on multivariate high-frequency time series.



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Research Interests:
Biological devices & systems, BioMEMS, Electronic devices, Electronics, Energy, Energy harvesting devices & systems, Medical devices & systems, Photovoltaics, Power management, Sensors.

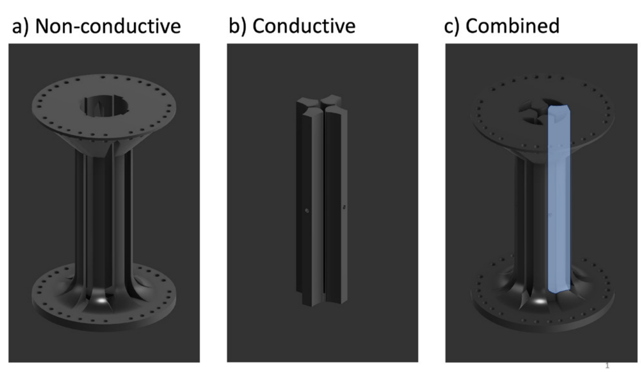
Exploring Material Extrusion for High-Precision, Compact Mass Spectrometry

5.06

A. Diaz

Sponsorship: MIT Portugal Program, Flagship Project NewSat

Mass spectrometry (MS) is the gold standard for quantitative chemical analysis. However, mainstream mass spectrometers are large, heavy, and power hungry, restricting their ability to be deployed into in-situ, portable, and hand-held scenarios, e.g., drones, CubeSats. Via additive manufacturing, it is possible to create monolithically and more precisely complex objects, e.g., mass filters with better shaped and spatially arranged electrodes. Also, additive manufacturing is compatible with in-space manufacturing (it is very expensive to put a mass in orbit—3D printing greatly reduces material waste). There are reports of 3D-printed quadrupoles for mass spectrometry, but they are not monolithically made. In this study, we explore multi-material extrusion & custom RF hardware for precise, compact, low-power, deployable mass spectrometry.



▲ (a) Non-conductive exterior housing for the hyperbolic rods. (b) Conductive electrically isolated hyperbolic rods. Diameter between the hyperbolic rods is 4 mm. (c) shows a and b together (printed simultaneously) with one of the rods highlighted.

One-Class Anomaly Detection Using Kernel Density Estimation Methods for Semiconductor Fabrication Processes

5.07

R. Owens, F.-K. Sun, C. Lang, B. Lawler, D. S. Boning

Sponsorship: Analog Devices, Inc.

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Research Interests:
Artificial Intelligence, Electronic devices, Electronics, Nanomanufacturing.

In semiconductor fabrication processes, undetected faults can be extremely costly. Machine learning has allowed for advances in fault detection and classification, but there are still difficulties in applying these techniques to the monitoring of fabrication processes. Concept drift, infrequency of faults, and differences between processes, tools, and recipes all present challenges distinct to the semiconductor industry.

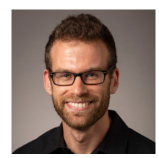
In this work, we present a one-class time series anomaly detection method that uses univariate sensor data to detect faults in semiconductor fabrication processes. The proposed method uses kernel density estimation (KDE) to create probability distributions for nominal process runs. Incoming sensor data can then be compared to these trained distributions to determine the likelihood that the new signal is nominal or anomalous. Critically, the use of a first-in, first-out queue for creating the probability distributions allows for the model to adapt to new conditions, thus overcoming the challenge of concept drift. The KDE method can be combined with techniques for transfer learning, which enables startup of the anomaly detector with as little as 25 previous process runs. This allows for model information to be transferred between similar tools or recipes, even ones that are used infrequently. We also consider the use of dynamic time warping to improve the accuracy of the sensor probability distributions. The proposed KDE methods are tested on historical data from plasma etch and ion implantation processes, outperforming benchmark methods including traditional statistical process control (SPC), one-class support vector machine (OC-SVM), and variational auto-encoder (VAE) based detectors.

Ultra-fast Absorption of Gas Bubbles using Nanoengineered Capture Surfaces

5.08

J. R. Lake, V. J. Leon, T. Joseph, S. Khan, K. K. Varanasi

Sponsorship: National Science Foundation Graduate Research Fellowship under Grant No. 1122374



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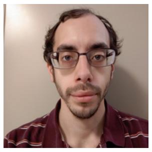
Research Interests:
Energy, Energy harvesting devices & systems, Fuel cells.

Gas absorption by a liquid media is an essential part of many large-scale industrial processes. When gas is injected into an absorber unit as discrete bubbles, as is the case for bubble column absorbers or gas sparging systems, the effectiveness of their reaction relies on careful control of the bubbles' properties and flow. Here we demonstrate efficient gas absorption into a liquid by using engineered surfaces that manipulate bubbles and enhance the reaction rate between the phases. By integrating these surfaces into a gas-absorbing system, we are able to increase the reaction rate by 2 orders of magnitude compared to a surfaceless gas-absorbing system. Experimentally we use carbon dioxide gas and a moderately alkaline potassium hydroxide absorbent solution. A surfaceless system suffers from two disadvantages: (1) bubble reaction rate decreases as they shrink and (2) the bubbles do not fully absorb due to product aggregation on their surface, blocking the gas/liquid reaction interface. However, our method overcomes the said challenges by (1) demonstrating the highest reaction rates for smaller bubbles, reversing the aforementioned trend, and (2) benefiting from the rapid timescales of bubble-manipulation relative to product aggregation, consequently avoiding the aggregation regime and leading to complete gas absorption. Finally, we offer to integrate bubble-manipulating surfaces in liquid gas-absorbing systems as an absorption technique with advantageous scaling for small-scale or distributed modular absorber designs.



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2D materials, Batteries, BioMEMS, Electronic devices, Electronics, Energy, Field-Emitter devices, Fuel cells, Integrated circuits, Lasers, MEMS & NEMS, Microfluidic devices & systems, Molecular & polymeric materials, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Photovoltaics, Quantum devices, SiGe and Ge, Spintronics, Thermal structures, devices & systems, Transducers.

3D-Printed, Miniature Time-Of-Flight Reflectron Mass Spectrometer

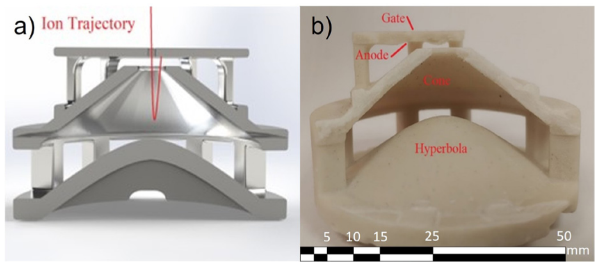
5.09

N. Lubinsky, C. Eckhoff, L. Velásquez-García

Sponsorship: Empiriko Corporation

Compact mass spectrometry is driven by a broad range of fields where portability, low mass, and reliable analytical chemical sensing are chief driving factors. There are numerous reports of semiconductor microfabricated mass filters for compact mass spectrometers. However, additive manufacturing surpasses semiconductor fabrication for creating finely featured, freeform, miniaturized, complex objects in novel materials.

In this project we are developing the first additively manufactured, miniature, monolithic reflectrons for compact mass spectrometry. Devices are 3D-printed in glass-ceramic via vat polymerization with selected surfaces electroplated. Our reflectron design involves a hyperbolic electrode encased by a grounded cone, a gate electrode for ionic flow, and an anode for reflected ions (Figure 1). This configuration enforces a quadratic-scaling potential and reflects all ions independent of initial energy.



◄ (a) Cross-section of CAD model of the reflectron showing ion trajectory and (b) cross-section of 3D-printed reflectron with labeled surfaces that are plated to create a working device.

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Robust Bayesian Optimization for Integrated Photonics

5.10

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Photonic integrated circuits are a promising platform for a wide range of applications, from quantum information processing to biosensing. However, packaging of photonic integrated circuits presents many challenges, such as achieving low-loss coupling of light from fibers (large optical modes) to on-chip waveguides (small optical modes). Novel design of fiber-chip couplers is an area of great interest for the future of photonic packaging. Optimizing the performance of couplers and other photonic devices using gradient-free heuristics typically requires the repeated use of the finite-difference-time-domain (FDTD) method to solve Maxwell's equations at a large number of discrete mesh points. However, FDTD simulations can be extremely time-consuming, necessitating alternative methods to optimize device designs using fewer simulations. Bayesian optimization has emerged as a computationally-efficient approach which relies on Gaussian process regression to build surrogate models that predict device performance and thus significantly reduce the number of time-consuming FDTD simulations. It is essential to optimize photonic devices not only to maximize their peak performance, but also to render them robust to fabrication process variations. Here, we explore robust Bayesian optimization methods that allow the user to specify a trade-off between the device's peak performance and its insensitivity to parameter variations. We apply our methods to the design of photonic structures such as fiber-chip couplers, and evaluate the variation-insensitivity of devices optimized using our robust Bayesian algorithms.

Gd Dependence of Dzyaloshinskii-Moriya Interaction in Rare-earth Transition-metal Amorphous Ferrimagnets

5.11

D. Suzuki, G. S. D. Beach

Sponsorship: DARPA

Spintronics provides promise for next generation memory storage technologies based on chiral spin textures such as skyrmions or homochiral domain walls. Chiral spin textures are stabilized by the Dzyaloshinskii-Moriya Interaction (DMI), an indirect exchange interaction arising from broken inversion symmetry and by high spin-orbit coupling in an adjacent heavy metal layer. As a result, control of DMI is critical to engineering spintronic devices. Amorphous rare-earth transition-metal ferrimagnets are a technologically interesting class of spintronic materials due to their small stray fields relative to ferromagnets, resulting in smaller skyrmions, and high domain wall velocities in films near their angular momentum compensation point. Previous work has measured the DMI using different heavy metal layers in ferro- and ferrimagnetic systems, however, the DMI resulting from ferrimagnet/heavy metal interfaces has yet to be fully explored. In particular, the rare-earth element's contribution to DMI is not well understood in rare-earth transition-metal ferrimagnets. In this study, we measure the DMI as a function of Gd content in Pt/GdCo thin films. The DMI is determined by domain wall motion experiments in magnetic racetrack devices. We find that the DMI strength has a non-monotonic dependence on Gd content and is proportional to the net spin density of the ferrimagnet. This suggests that the addition of Gd impacts the Pt/Co interaction and provides new insight into the design of spintronic materials for with optimized chiral spin textures.

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Additively Manufactured, Compact Quadrupole Mass Analyzer

5.12

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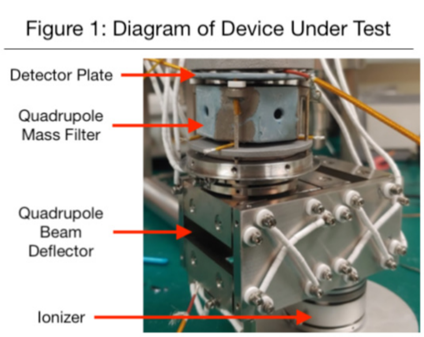
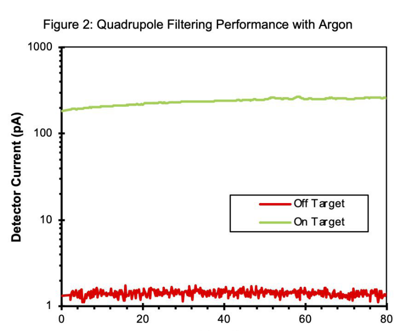
Sponsorship: Empiriko Corporation

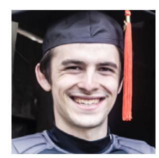
Mass spectrometry is a powerful tool for analyzing matter. As one of the most widely used and versatile scientific instruments, there is a growing need for high-quality portable mass spectrometers. The purpose of this project is to demonstrate the utility of additive manufacturing (AM) techniques for implementing miniature mass spectrometer systems. With special design techniques emabled AM, we have designed and fabricated the world's first monolithic, additively manufactured, compact quadrupole mass filter (Figure 1). The quadrupole features a monolithic design which aligns the four electrode rods without any need for assembly, and the part is produced using digital light processing of printable glass-ceramic feedstock. Then, the part is metallized with electroless nickel-boron all over, except at certain structural locations with maskant applied. This keeps the four rods galvanically isolated. With the device in vacuum, ionized argon is fed on one side of the quadrupole and detected by a Faraday cup. We observe two orders of magnitude of difference in detector current when the quadrupole fields are set to transmit or reject argon, respectively (Figure 2).



▲ Figure 1. Diagram of Device Under Test.



▲ Figure 2. Quadrupole Filtering Performance with Argon.



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Text Mining of CVD Synthesis Recipes for 2D Materials by Natural Language Processing

5.13

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Sponsorship: U.S. Army Research Office through the Institute for Soldier Nanotechnologies at MIT

Tremendous and precious scientific knowledge is written in text format as journal articles. This enormous unstructured data is challenging for humans to analyze and develop comprehensive perspectives from the past. Recently, natural language processing (NLP) has made significant advances in word embedding, especially with the launch of pre-trained models (e.g., BERT, GPT). Materials science has attempted to apply this breakthrough by converting unstructured data into structured data, but so far this is limited to very general methods and materials, and the provided information is not yet beyond researchers' domain knowledge. In this work, we adopt the state-of-art NLP technique to collect synthesis recipes from journal articles for seven low-dimensional materials, including CNT, graphene, hexagonal boron nitride (hBN), molybdenum disulfide (MoS_2), molybdenum diselenide ($MoSe_2$), tungsten disulfide (WS_2), and tungsten diselenide (WSe_2). First, we deploy a fine-tuning BERT model without manual annotation by calculating the term frequency of the titles and combining them with our prior knowledge, allowing us to extract CVD-related titles. Furthermore, we apply keyword searching fusion with a fine-tuning BERT model to classify the CVD abstract as *Correlation Output*, such as monolayer, bilayer, multilayer, and nanostructures. Lastly, we implemented the BERT model for named entities recognition (NER) to extract experimental recipes as *Correlation Input*. Through statistical analysis, we discover the correlation among the recipes and their results for each material and unravel the synthesis trajectory between different materials. Our work may serve as a methodology for applying natural language processing in optimizing existing 2D materials and accelerating the exploration of new advanced materials.

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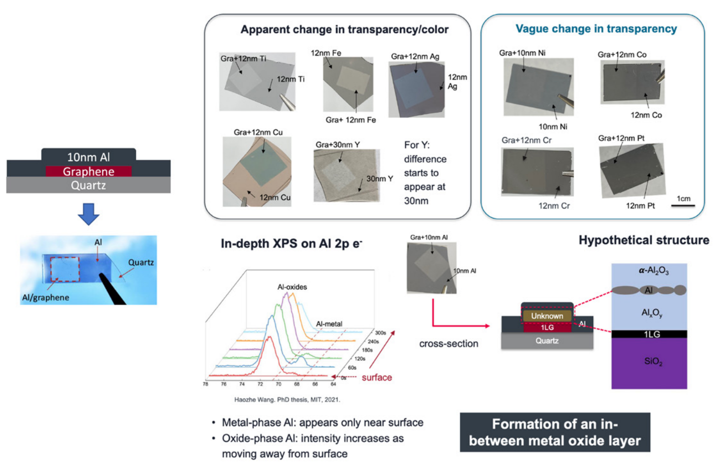
2D materials, Nanomaterials, Graphene, Chemical Vapor Deposition.

Metal-graphene Interface in Evaporative-deposition Growth of Various Metals on Graphene

5.14

Z. Wang, H. Wang, J. Zhu, T. Pieshkow, X. Zheng, S. A. Vitale, Y. Han, J. Kong

Graphene, the first member in 2D materials family, has very unique electrical, optical and mechanical properties, which opens up vast opportunities for applications. The understanding of metal-graphene interface is crucial for many research and applications, but hasn't been understood thoroughly due to the difficulty in characterization. Here we observed that when depositing 8-15 nanometers metal onto CVD (chemical vapor deposition) grown graphene, for certain types of metal there is a change in optical contrast compared to the area without graphene underneath, but for others such change is not noticeable. In this work we carried out various investigations to understand the reasons behind the phenomena and explored their potential applications.



▲ Optical Images of different types of metals deposited on graphene. XPS result of 15nm Al deposited on graphene to show the existence of oxygen at the interface.

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Nanotechnology, Spintronics.

Coherent Magnon-induced Domain Wall Motion in a Magnetic Insulating Channel Device

6.01

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Sponsorship: SMART Center, NSF DMR1808190.

Spintronics devices are CMOS compatible memory and logic devices that use both magnetic and electric charge to operate. They offer less power consumption, more scalability, and faster operation for semiconductor devices. Developing these devices requires understanding of various magnetic phenomena that occur in magnetic materials, including spin waves and domain walls.

Spin waves can travel up to macroscopic distances in low-damping materials and can impart angular momentum to domain walls via spin transfer torque. Spin-wave-driven domain wall motion offers a “switching” mechanism for spintronics devices and has already been demonstrated in magnetic metals; however, it has yet to be studied in insulators. Bismuth-substituted yttrium iron garnet (BiYIG) is a type of ferrimagnetic insulator with low damping allowing for long spin wave decay lengths and high domain wall velocities. Plus, its insulating properties reduce joule heating or conduction electron related dissipation. In this work, the interactions between spin waves and domain walls are observed and characterized in BiYIG. RF pulses around the resonance frequency of BiYIG most effectively excite spin waves that translate these domain walls. At zero applied magnetic field, a magnon spin current excited by an RF pulse as short as 1 ns can reliably move a domain wall over 15 μm distances, requiring only a few picojoules of energy for the process. The low power consumption and fast dynamics of spin wave induced domain wall motion in BiYIG facilities spintronics device applications to improve the energy efficiency and speed of modern computation.

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Research Interests:
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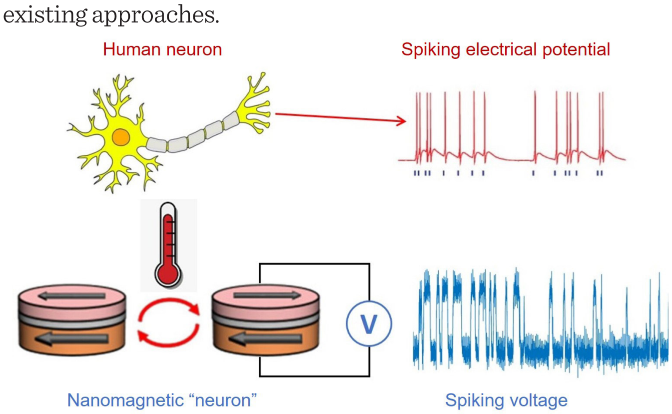
Neuromorphic Computing with Probabilistic Nanomagnets

6.02

B. C. McGoldrick, M. A. Baldo, L. Liu
Sponsorship: EECS Mathworks Fellowship

The human brain is capable of performing complex tasks such as object recognition and inference, all while operating at low power. In contrast, performing the same tasks on digital computers requires significant energy, time, and hardware. While the brain exhibits random, noisy behavior, digital computers are designed oppositely to be deterministic and low-noise. By emulating the brain's probabilistic nature in hardware, we can potentially achieve superior speed and energy-efficiency on solving the aforementioned problems. We develop a probabilistic bit (p-bit) based on a nanomagnetic device that produces a random bipolar voltage signal driven by ambient thermal noise. We can control the p-bit's probability and fluctuation rate by applying magnetic fields or charge currents. Finally, we elucidate a plan to integrate our tunable p-bits with traditional CMOS circuits to realize a probabilistic inference system with potentially greater speed and energy efficiency than existing approaches.



▲ Nanomagnetic “neuron” that converts ambient thermal fluctuations at room temperature to a random, fluctuating bipolar voltage signal. This behavior can be likened to the random spiking behavior of a neuron in the human brain.

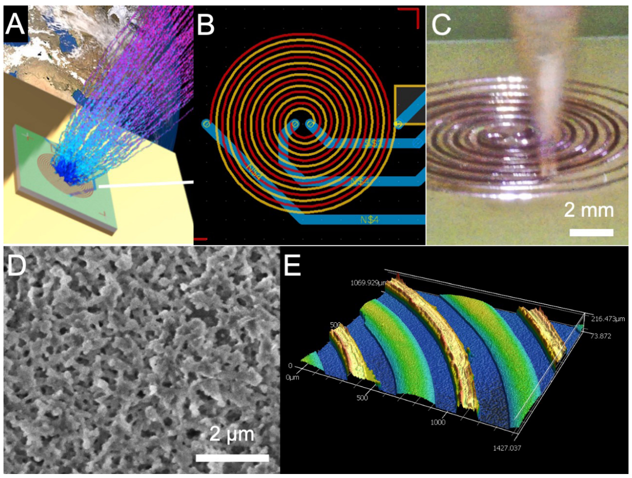
High-Density Additively Manufactured Carbon Nanotube Field Emission Electron Sources

6.03

A. Kachkine, L. F. Velásquez-García

Sponsorship: NewSat Project, MIT Portugal program, Voltera

Ion thrusters for satellites in low earth orbit require charge neutralization to avoid self-degradation; field emission (FE) electron sources have the necessary oxygen tolerance and power efficiency to ensure low-cost, low-weight integration. Despite their superiority over conventional thermionic ones, the high cost of cleanroom fabrication has limited FE source applications. We present high-performance FE sources made via direct ink writing of a custom, high-concentration carbon nanotube ink on a printed circuit board. Our spiralized devices have a 65% larger current density and 35% lower startup voltage compared to the state-of-the-art. These FE devices enable next-generation ion thruster neutralizers and miniature x-ray sources.



◄ A) Spiralized FE source showing out-of-plane electron emission. B) Spiralized FE source design, with concentric emitting and extractor electrodes. C) Fabrication via direct ink writing. D) Scanning electron microscopy of printed carbon nanotube clusters. E) Topological map showing trace uniformity.

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Artificial Intelligence, Batteries, Biological devices & systems, BioMEMS, Displays, Electronic devices, Electronics, Field-Emitter devices, Integrated circuits, Lasers, Light-emitting diodes, Machine Learning, Medical devices & systems, MEMS & NEMS, Microfluidic devices & systems, Molecular & polymeric materials, Nanotechnology, Optoelectronics, Photonics, Photovoltaics, Quantum devices, Sensors, Systems, Thermal structures, devices & systems.

Energy-efficient Ising Machine Based on Stochastic Computing

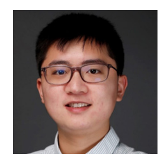
6.04

Q. Wang, B. C. McGoldrick, M. A. Baldo, L. Liu

Sponsorship: Harvard Graduate School of Arts and Sciences Prize Fellowship

Hardware realization of Ising machines in both analog and digital domains are gaining broad interest recently, for their ability to outperform CPU and GPU in solving a range of combinational optimization problems. Analog circuit components, such as memristors or phase-transition nano-oscillators, are proposed to be much more energy-efficient, but current architectures requiring heavy peripheral circuits limit large scale integration. By contrary, digital CMOS accelerators can easily scale up, but further performance improvement is challenging as we are reaching the end of Moore's Law. Efficient digital-analog hybrid architecture, which can harvest the ultra-efficient computing ability of emerging nano devices while keeping the scalability of digital circuit, is under urgent demand not only for practical applications, but also provides inspirations for next-generation computing.

In this work, we propose an unconventional Ising machine architecture based on stochastic computing. Multiplication operations – the most computationally expensive part of CMOS digital annealers – are replaced by single XNOR gates. On the other hand, the most consuming part of any stochastic computing approach, which is the random number generator, is replaced by stochastic magnetic tunnel junction (sMTJ). Preliminary test results on an entry-level FPGA chip show energy-to-solution metrics comparable to the best values reported so far, which can be further improved by integrating sMTJ into our system. Our design naturally adopts the benefits of two industrially accessible technology – digital CMOS and MRAM, suggesting that sMTJ has the potential to enable large-scale integration of power-efficient unconventional computing engines.



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Research Interests:
2D materials, Artificial Intelligence, Electronic devices, Integrated circuits, Nanomaterials, Nanotechnology, Quantum devices, Spintronics, Neuromorphic computing.

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2D materials, Electronic devices, Electronics, Energy, Energy harvesting devices & systems, Lasers, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Quantum devices, Sensors, Spintronics.

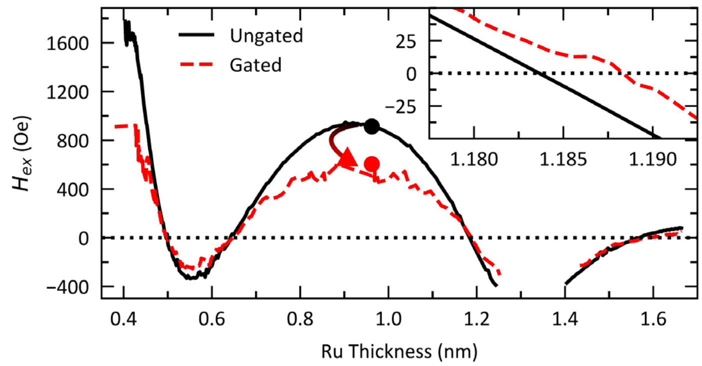
Voltage-Control of Magnetic Order in RKKY Coupled Multilayers

6.05

A. E. Kossak, M. Huang, P. Reddy, D. Wolf, G. S. D. Beach

Sponsorship: NSF, SRC, DFG

In the field of antiferromagnetic (AFM) spintronics, there is a significant effort present to make AFMs viable active components for efficient and fast devices. Typically this is done by manipulating the AFM Néel vector. Here we establish a novel method of enabling AFM active components by directly controlling magnetic order. We show that magneto-ionic gating (MIG) of hydrogen enables dynamic control of the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction in solid-state synthetic-AFM multilayer devices. We tune the RKKY interaction to drive continuous transitions from AFM to FM, and vice versa. The switching is sub-millisecond at room temperature and fully reversible. We validate the utility of this method by demonstrating that MIG of the RKKY interaction allows for 180 field-free deterministic switching. This novel, dynamic method of controlling a fundamental exchange interaction can engender the manipulation of a broader array of spin textures e.g. chiral domain walls and skyrmions.



▲ Magneto-ionic gating of the RKKY interaction of a [Co/Pt]/Ru/[Co/Pd] multilayer heterostructure as a function of Ru wedge thickness at +4 V. The arrow indicates the ability to significantly change the exchange field of a single device.

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Role of Local Gyrotropic Force in Distortion-limited High-speed Dynamics of Antiferromagnetic Skyrmion

6.06

E. A. Tremsina, G. S. D. Beach

Sponsorship: NSF GRFP and DARPA TEE Program, SMART, one of seven centers of nCORE, a Semiconductor Research Corporation program, sponsored by NIST

Magnetic solitons, quasiparticles formed by a local twist in the magnetization, are great candidates for use in novel spintronic devices. The key question for their use in practical applications, however, is the maximum speed of propagation through magnetic media. For one-dimensional solitons (domain walls), the high-speed dynamics are well understood and are limited in antiferromagnetic materials by relativistic-like effects, namely velocity saturation towards a speed akin to the speed of light, and Lorentz-like width contraction. Two-dimensional solitons (skyrmions) instead exhibit elliptical distortions followed by a full breakdown at a critical limiting velocity, and the exact nature of this process is yet to be understood. Here, the unique capabilities of a fully atomistic model are used to perform an extensive and systematic study of soliton dynamics. As a result, a physical explanation for skyrmion deformations, which are attributed to the local imbalance of the gyrotropic forces, is derived using numerical simulation data. It is shown also that the inherent skyrmion structure impedes their ability to even reach the velocity regime where relativistic effects could begin to occur. These results expand the understanding of the fundamental properties of magnetic skyrmions, in particular, their dynamical stability at high speeds, as well as their potential use for spintronic applications.

Modellng Interfacial Competition on Drug Crystal Surfaces Using Molecular Dynamics Simulations

6.07

D. Nguyen, L. Attia, D. Gokhale, P. S. Doyle

Sponsorship: MIT UROP Office

Oral administration is often preferred among all drug administration routes due to its simplicity, low cost, and convenience. However, nearly 90% of drug candidates in the pharmaceutical development pipeline have high hydrophobicity, which significantly hinders their dissolvability in the gastrointestinal (GI) tract and limits bioavailability. Our lab has developed a suite of 'bottom-up' methods to template drug nanocrystals by embedding APIs in polymeric matrices as an approach to reduce drug aggregate sizes for improved bioavailability. However, recent experimental results have motivated the need for a mechanistic understanding of the influence of excipient-drug interactions during processing.

In this work, we present the use of molecular dynamics (MD) simulations to advance understanding of how molecular interactions between excipients and drug control the self-assembled nanostructure on drug crystal surfaces. MD is used to explore the compositional effects of surfactant and polymer excipients interacting on the surface of a model hydrophobic API (fenofibrate). The role of surfactant in screening polymer-drug interactions is elucidated as an important mechanism for designing 'bottom-up' small molecule formulation processing schemes. Based on the results of this work, various combinations of drugs, surfactants and polymer matrices can be tested computationally and experimentally, leading to the next generation of oral drug delivery forms.

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Biological devices & systems, Microfluidic devices & systems, Molecular & polymeric materials, Nanomanufacturing, Nanomaterials, Nanotechnology, Thermal structures, devices & systems.

Investigating the Line Shape of Indium Phosphide Quantum Dots

6.08

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Sponsorship: Samsung

InP quantum dots (QDs) have emerged as a promising material for QD light-emitting diodes due to their high photoluminescence quantum yields, avoidance of toxic materials, and tunable emission energies. QD light-emitting diodes seek to combine vivid colors, with high brightness without light bleed and saturated blacks that can accompany organic light-emitting diode displays. While CdSe has been studied for these purposes, their implementation has been limited due to their toxicity. While InP QDs have emerged as a material of interest, they are spectrally broader than their CdSe analogues. This is undesirable for light-emitting applications as it reduces the color purity. Optimizing the color purity of QDs requires understanding the mechanisms of spectral broadening. While ensemble-level broadening can be minimized by synthetic tuning to yield monodisperse QD sizes, single QD linewidths are broadened by elastic/inelastic exciton-phonon scattering and fine-structure splitting. For the first time, we have reconciled narrow low-temperature linewidths and broad room-temperature linewidths within a self-consistent model that enables parameterization of linewidth broadening, for different material classes. Our findings reveal that red-emitting InP/ZnSe/ZnS QDs have intrinsically narrower linewidths than typically synthesized CdSe QDs, suggesting that these materials could be used to realize QD light-emitting diodes with unprecedented color purity. Thus, InP quantum dots have the potential to substantially transform the QD light-emitting diode as a non-toxic material that can enhance the sharpness of color displays.

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Displays, Energy, Light-emitting diodes, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics.

6.09

Predicting Coherent Nanocrystal Orientation in Nanocrystal Superlattices by Minimizing Ligand Packing Frustration.

E. K. Price, W. A. Tisdale

Sponsorship: DOE Office of Science, Basic Energy Sciences, NSF

Semiconducting, colloidal nanocrystals (NCs) have size-tunable optical and electronic properties and show promise for next-generation sensing, photovoltaic, and computing devices. For integration into optoelectronic devices, NCs are assembled into ordered superlattices (SLs). Since the SL structure can influence charge and thermal transport in these devices, robust engineering control over SL formation is needed. A number of factors influence the self-assembly of colloidal NCs, including the well-studied impacts of nanocrystal size and shape. In recent years, the importance of both bound and unbound organic ligands on self-assembly outcomes has been highlighted; the ligand length, ligand coverage, bound and unbound ligand fractions, and ligand interactions can all influence the resulting NC SL structure. In this work, we consider how the classic influence of nanocrystal shape can impact ligand packing frustration and influence the coherent orientation of non-spherical NCs in NC SLs. Through the application of the freely jointed chain model to estimate conformational entropy, we find that minimizing the packing frustration of the ligand layer may explain experimental observations of NC alignment in NC SLs. We validate our model by comparing to published X-ray scattering data showing the kinetics of lead sulfide (PbS) superlattice formation. These data show that as solvent is evaporated, the SL exhibits a Bain-like distortion, contracting from an fcc to bcc configuration, and the coherent NC tilt relative to the substrate changes from 9.7° to 0°. The thermodynamic understanding of coherent NC orientation in NC SLs explored in this work may inform the synthesis of high-quality films with minimal disorder for integration into optoelectronic devices and enable the experimental realization of predicted theoretical properties such as band-like transport in NC SLs.

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Research Interests:
2D materials, Electronic devices, Nanomaterials, Nanotechnology, Optoelectronics, Sensors.

6.10

Large-Scale Gold-Assisted Exfoliation and Transfer from Semiconducting and Metallic Bulk Crystals to 2D Monolayers

S.-Y. Tang, T. Zhang, J. Kong

Sponsorship: Graduate Students Study Abroad Program, National Science and Technology Council, Taiwan

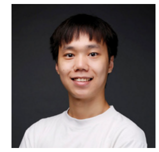
Two-dimensional layered materials have attracted intense interest because of their unique electrical and optical properties and became promising candidates for electronic and optoelectronic devices as well as low-cost catalysts for energy generation. It is crucial but still challenging to achieve uniform and defect-free monolayers with high yield and large area by the conventional mechanical exfoliations. Here, we investigate a gold-assisted exfoliation and transfer methods to produce large-scale 2D semiconducting and metallic monolayers from bulk crystals based on the strong van der Waals force at the clean interface of Au (111) and 2D layered crystals according to previous studies and predictions. The addition of PMMA supporting layer between thermal release tape (TRT) and gold film in our approach allows the effective exfoliation from uneven or irregular crystal surfaces and the improvement in uniformity and size of single-crystalline monolayers compared to the typical Scotch-tape exfoliation method. Moreover, the exfoliated monolayers can be easily transferred to arbitrary substrates. This research suggests the potential to produce continuous 2D monolayers up to millimeter scale and enables further integration of these atomically thin materials to a wide range of potential applications.

Chemical Vapor Deposition Synthesis of Multilayer Hexagonal Boron Nitride

6.11

H. Liu, Z. Luo, J. Kong

Sponsorship: EECS Faculty Research Innovation Fellowship.



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Research Interests:
2D materials, Electronic devices, Nanomaterials, Nanotechnology.

Hexagonal boron nitride (hBN) has attracted tremendous research interest due to its wide band gap of up to ~6 eV, remarkable chemical and physical stability, atomic surface flatness, etc. As such, hBN serves as a promising candidate as quantum emitters, insulators, or support for the next generation of electronic and photonic devices. Recent reports on the wafer-scale synthesis of hBN are limited to monolayer or few layers, which is due to the self-limited growth regime for the growth substrates with low nitrogen solubility. However, monolayer or few-layer hBN is limited in its performance, some of the problems include unstable optical emission, non-satisfied mechanical strength, inability to screen out substrate effects, etc. In this work, we propose to utilize single crystalline metal alloys as the growth substrate to synthesize multilayer hBN by chemical vapor deposition. The uniformity of both substrates and the as-synthesized hBN films will be characterized by optical contrast and Raman spectroscopy mapping. The crystallinity of the hBN films will be characterized by XRD and the full width at half maximum of Raman peaks corresponding to hBN. Atomic force microscopy will be used to measure the hBN thicknesses and electron microscopy will be conducted to reveal the microstructure of hBN films. The success of this work will help to improve the next generation of 2D materials-based electronic devices, finally leading to a world with a higher information transport rate with less energy consumption compared to the current Si-based devices.

Nonplanar Nanofabrication via Interface Engineering

6.12

S. O. Spector, P. F. Satterthwaite, F. Niroui

Sponsorship: NSF Graduate Research Fellowship, Samsung Electronics Fellowship

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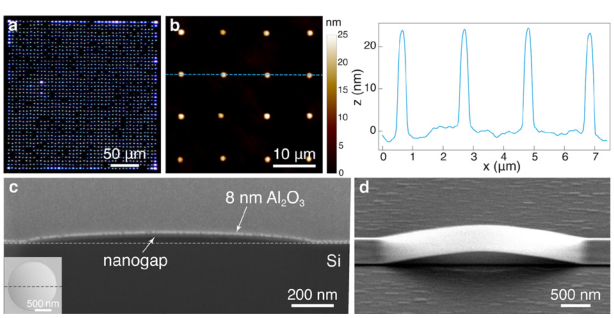
Research Interests:
Electronic devices, MEMS & NEMS, Nanomaterials, Nanotechnology.

Nonplanar nanostructures, composed of suspended ultrathin films and nanogaps, are foundational for next-generation miniaturized nanoelectromechanical devices, photonic elements, and metamaterials. However, resolution constraints and instabilities due to nanoscale forces limit their fabrication through conventional top-down techniques.

This work reports a new approach for scalable fabrication of suspended, ultrathin nanostructures with controlled nanoscale gaps, without the use of a sacrificial layer. We engineer surface adhesive forces through a patterned molecular monolayer to enable controlled delamination of an oxide thin-film in predetermined locations. By extending standard, wafer-scale, and conventionally-compatible planar fabrication techniques, we form nonplanar structures with thicknesses < 10 nm and nanogaps reaching < 10 nm. Using this approach, we demonstrate an application in ultrathin mechanical resonators that could be used for sensitive mass spectroscopy.



▲ (a) Darkfield image of an array of dome-shaped Al2O3 nanostructures. (b) AFM and line scan of a nanostructure array. (c) Cross-sectional SEM of a fabricated 8 nm-thin suspended membrane. (d) SEM of a doubly clamped, 8 nm-thin mechanical resonator.

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Research Interests:
2D materials, Actuators, Electronic devices, MEMS & NEMS, Molecular & polymeric materials, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Sensors.

Van der Waals integration Beyond the Limits of Van der Waals Forces

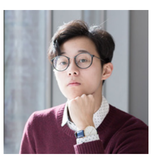
6.13

P. F. Satterthwaite, W. Zhu, P. Jastrzebska-Perfect, M. Tang, H. Gao, H. Kitadai, A-Y. Lu, Q. Tan, J. Kong, X. Ling, and F. Niroui

Sponsorship: NSF Center for Energy Efficient Electronics Science (E3S) (ECCS-093951), NSF EAGER (2135846), NSF Graduate Research Fellowship Program (1745302)

Fabrication of pristine van der Waals (vdW) interfaces between two-dimensional (2D) and other materials are essential for emerging optical and electronic devices. The weak vdW forces at the interface of interest cannot, however, be readily tuned to enable the direct integration of arbitrary materials. Conventionally, this is addressed by transferring the 2D material using sacrificial layers, solvents, and high temperatures, introducing damage and contaminants. Conventional device integration further requires post-transfer fabrication, often leading to device performance influenced by processing artifacts rather than solely reliant on the intrinsic materials' properties.

Here, we introduce a new fabrication platform, adhesive matrix transfer, which enables direct 2D material-to-device integration in a single, dry step. This is achieved by decoupling the forces promoting the transfer from those at the vdW interface of interest. We use this approach to demonstrate conventionally-forbidden direct integration of 2D semiconductors with bulk dielectrics. Pristine MoS_2 transistors are further fabricated through direct exfoliation of MoS_2 monolayers onto device structures, highlighting the ability of our platform to enable single-step 2D material-to-device integration. The prospects of using this platform for flexible electronics are further discussed.



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Research Interests:
Nanomanufacturing, Nanomaterials, Nanotechnology, Quantum devices.

Contact Printed Nanoparticles as Building Blocks for Active Nanodevices

6.14

W. Zhu, P. F. Satterthwaite, P. Jastrzebska-Perfect, R. Brenes, F. Niroui

Sponsorship: NSF Award CMMI-2135846

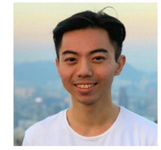
Nanoparticles, efficiently formed through bottom-up synthesis with diverse compositions, structures, and functionalities, exhibit unique properties compared to their top-down fabricated counterparts. Leveraging these properties requires deterministic patterning of nanoparticles. Here, we present a versatile, scalable, and pristine approach for the deterministic integration of nanoparticles into active structures and devices with single-particle resolution. In our approach, named nanoparticle contact printing, nanoparticles are first spatially assembled into a topographical template, then printed onto diverse surfaces and interfaces. By engineering interfacial interactions, our approach promotes high-yield nanoparticle transfer without requiring solvents, surface treatments, or sacrificial layers as is conventionally needed. With our approach, surfaces remain pristine and are accessible for integration into functional structures. We demonstrate this through a particle-on-mirror plasmonic cavity model system, where >2000 gold nanocubes are deterministically patterned onto template-stripped gold with sub-50 nm positional accuracy and minimized inter-structural variability. We further highlight the integration opportunities offered by our technique by fabricating arrays of emitter-coupled nanocavities. In addition, we use this platform to demonstrate mechanically-active molecular junctions with sub-nm tunability. This opens up diverse opportunities for new applications in sensors, actuators, and reconfigurable optical devices and systems.

Multiplication of III-V Membranes by In-Situ Graphene Growth

6.15

N. M. Han, H. Kim, Y. Liu, K. Lu, C. Chang, J. Kim

Sponsorship: AFRL (FA9453-18-2-0017 and FA9453-21-C-0717), DARPA (029584-00001), DOE (DE-EE0008558)



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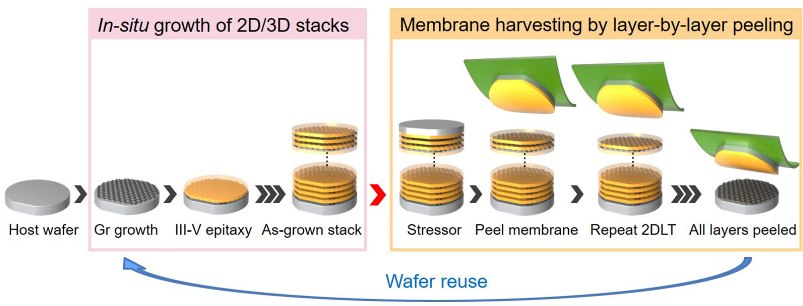
Research Interests:
2D materials, Biological devices & systems, Displays, Electronic devices, Electronics, GaN, III-Vs, Information processing, Integrated circuits, Lasers, Light-emitting diodes, Medical devices & systems, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Photovoltaics, Quantum devices, Sensors.

Single-crystal III-V compound semiconductors are important building blocks for functional devices due to their high electron mobilities, a wide range of bandgaps, and excellent optoelectronic properties. However, current methods to produce their freestanding membranes for heterointegration suffer from slow processes or poor material quality. Here, we demonstrate an approach to grow and harvest multiple wafer-scale single-crystal membranes by introducing weak van der Waals interfaces between epitaxial layers. This is achieved by directly growing graphene on III-V semiconductors in the MOCVD, which enables alternating growth of graphene and III-V semiconductor epilayers in a single run. Each epilayer in the multi-stack structure is then exfoliated to produce multiple freestanding single-crystal membranes with extremely high throughput from a single wafer, with a real potential of scaling up for low-cost solar cells, high-resolution LED displays, and next-generation wearable devices.



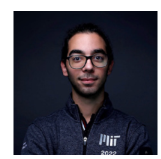
▲ Schematic of the single-crystalline membrane production process by in situ growth of multiple stacks of epilayer/2D layer and layer-by-layer exfoliation.

Locating Defects in Superconducting Nanowires

6.16

T. El Dandachi, E. K. Batson, S. Kandeh, R. Foster, M. Colangelo, K. K. Berggren

Sponsorship: Center for Quantum Networks



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Research Interests:
Electronic devices, Electronics, Information processing, Integrated circuits, Nanomaterials, Nanotechnology, Photonics, Quantum devices, Sensors, Simulation.

Superconducting nanowires (SN) are the leading technology for single photon detectors (SPDs) at infrared wavelengths and a promising candidate for low-energy electronics. The main factors limiting the scalability of nanowire devices are defects intrinsic to the material or that occur during fabrication. These defects, like grain boundaries or edge roughness, can locally reduce the maximum current a wire can carry before switching to the normal state. This leads to dark counts in SNSPD and unwanted switching behavior in electronics. Locating these defects through non-destructive microscopy techniques (e.g. SEM, AFM) is extremely challenging due to their reduced size (~ nm) with respect to the total area of the samples (~mm2). An alternative to microscopy is Time Domain Reflectometry (TDR), a technique that analyzes reflections in transmission lines to detect impedance mismatches. We demonstrate the working principle behind a modified version of TDR that takes advantage of the non-linearity of superconducting nanowires. This method detects defects by locally querying the switching current of the nanowire using two counterpropagating pulses. We send two pulses of opposite polarity from both ends of the wire. The pulses will cause the wire to switch only when the sum of their currents is above the switching current of the point where they intersect. The pulse magnitudes are chosen such that they don't individually switch the nanowire at any other point along the meander, allowing us to locally query the switching current at their intersection point only. We demonstrate this protocol on a 84 mm-long superconducting nanowire and construct a switching current vs position profile that can be used to infer the locations of unwanted defects. Further developing this technique would allow us to study defect formation, better characterize superconducting devices, and fix defects post-fabrication.

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Research Interests:
Artificial Intelligence, Information processing, Lasers, Nanotechnology, Optoelectronics, Photonics, Quantum devices, Si, Nonlinear optics.

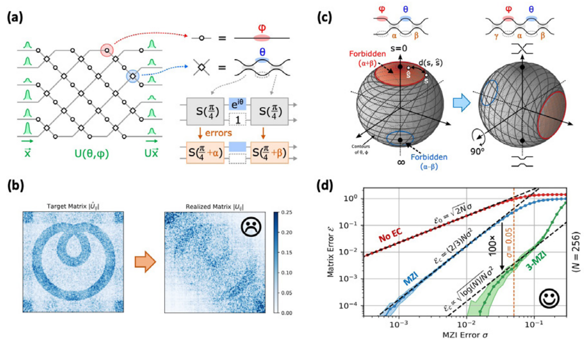
Asymptotically Fault-Tolerant Programmable Photonics

7.01

R. Hamerly, S. Bandyopadhyay, S. K. Vadlamani, D. Englund

Sponsorship: NTT Research, Inc. (R.H.), NSF GRFP (S.B.), AFOSR No. FA9550-20-1-0113, FA9550-16-1-0391 (D.E.)

Photonics is a promising platform for special-purpose computing, but is only competitive when scaled up to large circuits. Unfortunately, component errors limit the scaling of programmable photonic devices. These errors arise because the standard tunable photonic coupler---the Mach-Zehnder interferometer (MZI)---cannot be perfectly programmed to the "cross" state. Here, we introduce two modified circuit architectures that overcome this limitation: (1) a 3-splitter MZI mesh for generic errors, and (2) a broadband MZI+Crossing design for correlated errors. Because these designs allow for perfect realization of the cross state, the matrix fidelity no longer decreases with mesh size, allowing scaling to arbitrarily large meshes. The proposed architectures support progressive self-configuration, are more compact than previous MZI-doubling schemes, and do not require additional phase shifters. This eliminates a major obstacle to the development of very-large-scale photonic circuits.



◀ (a) 6x6 programmable photonic circuit. (b) Effect of component errors is to reduce circuit fidelity. (c) Proposed 3-MZI design, which shifts the "forbidden regions" away from the density peak. (d) Resulting 100x reduction in matrix error.

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Research Interests:
Information processing.

Noise Resilience Deep Reconstruction for X-ray Tomography

7.02

Z. Guo, Z. Liu, Q. Zhang, G. Barbastathis

Sponsorship: Singapore's National Research Foundation

X-ray tomography is a non-destructive imaging technique that visualizes the interior features of solid objects, with applications in biomedical imaging, materials science, manufacturing inspection, and other disciplines. Under limited-angle and low-photon sampling, a regularization prior is required to retrieve a high-fidelity reconstruction. Recently, deep learning has been used in X-ray tomography. The prior learned from training data replaces the general-purpose priors in iterative algorithms, achieving high-quality reconstructions with a neural network. Previous studies typically assume the noise statistics of testing data is acquired a priori from training data, leaving the network susceptible to a change in the noise characteristics under practical imaging conditions. In this work, we propose a noise-resilient deep-reconstruction algorithm for X-ray tomography. Our method improves the noise resilience of the learned prior by using low-noise simulation data for the training set. Through optimization with an objective function consisting of data-fidelity and sparse-prior (total variation) terms, noise-resilient MAP reconstructions are generated for UNet neural networks to acquire a noise-resilient prior distribution during training. Both simulation and experimental results show that utilizing MAP, instead of MLE and FBP, as the input reconstructions to the UNet improves the noise resilience of the learned prior at moderate photon counts per ray. Without training samples from different photon statistics, the MAP+UNet approach can produce acceptable reconstruction down to 50 photons per ray in simulations, and 214 per ray in experiments, whereas the FBP+UNet approach requires around 10x more photons per ray in simulations, and 2.5x more in experiments. The advantages of our framework may further enable low-photon tomographic imaging where long acquisition times may limit the ability to acquire a large training set.

Automatic Realization of Light Processing Functions for Programmable Photonics

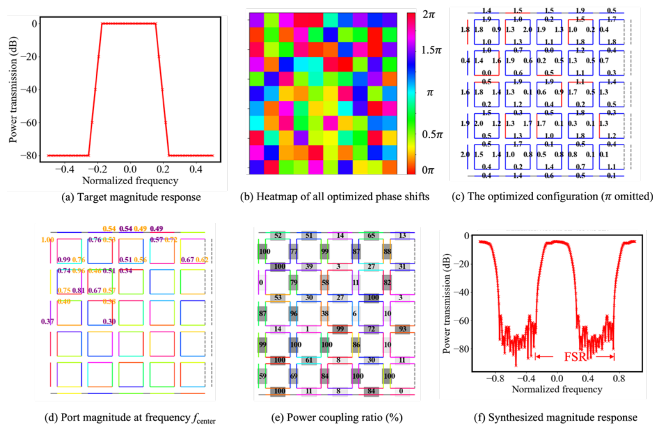
7.03

Z. Gao, Z. Zhang, U. Chakraborty, D. S. Boning

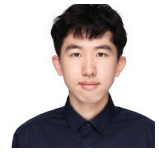
Collaborators: Xiangfeng Chen and Wim Bogaerts, Ghent University

Programmable integrated photonic circuits (PPICs) are an alternative paradigm to application-specific integrated photonics, exploiting run-time manipulation of light after a photonic chip is fabricated. Such reconfigurability is achieved by controlling active components (e.g., optical phase shifters) with electrical/thermal signals. Current published literature usually relies on hand-crafting to configure the PPIC so that certain light processing functions can be realized.

In this work, we have developed an automatic technique to implement light processing functions on a recirculating square-mesh PPIC. Our simulations demonstrate that our method can realize complex light processing functions in a matter of minutes and has the potential to work as a fundamental synthesis paradigm for programmable photonics.



▲ Synthesizing an optical filter on a 5-by-5 square programable photonics mesh.



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Research Interests:
Artificial Intelligence, Integrated circuits, Machine Learning, Photonics, Computer Aided Design, Design Automation.

Spectroscopy Signatures of Electron Correlations in a Trilayer Graphene/hBN Moiré Superlattice

7.04

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Sponsorship: STC Center for Integrated Quantum Materials, NSF

Two-dimensional (2D) materials, since its discovery in 2005, have attracted great interests among scientists. Especially, the idea of creating a moiré superlattice by stacking 2D materials vertically allows people to combine the properties of various 2D materials and to manipulate the electrons via electrostatic gating, making it a great platform to study exotic physics phenomena. Among them, ABC-stacked trilayer graphene / hexagonal boron nitride moiré superlattice (ABC-TLG/hBN) has been found as a promising system since it has large tunability and is free of twisting angle disorders. Currently, correlated insulator, superconductivity, and topological state have been reported in transport studies. However, the spectroscopic study of ABC-TLG/hBN is still absent, due to the size-mismatch between device dimension (typically ~ 10 um) and wavelength (30-100 um), which makes the signal-to-noise ratio very small. In this work, we report spectroscopy measurements of dual-gated ABC-TLG/hBN using a special Fourier transform infrared (FTIR) photocurrent spectroscopy method. We observe a strong optical transition between moiré minibands that narrows continuously as a bandgap is opened by gating, indicating a reduction of the single-particle bandwidth. At half-filling of the valence flat band, a broad absorption peak emerges at ~18 milli–electron volts, indicating direct optical excitation across an emerging Mott gap. Similar photocurrent spectra are observed in two other correlated insulating states at quarter- and half-filling of the first conduction band. Our work is the very first spectroscopic study of ABC-TLG/hBN system and provides key parameters of the Hubbard model for the understanding of electron correlation. Furthermore, this technique can also be applied to other graphene-based moiré systems that are also insufficient in spectroscopic studies and provide more insights to understand many exotic phenomena.

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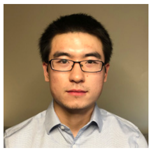
Research Interests:
2D materials, Artificial Intelligence, GaN, III-Vs, Lasers, Machine Learning, Photonics, Quantum devices, Spintronics.



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Research Interests:
Integrated circuits, Photonics, Numerical method, Machine Learning.

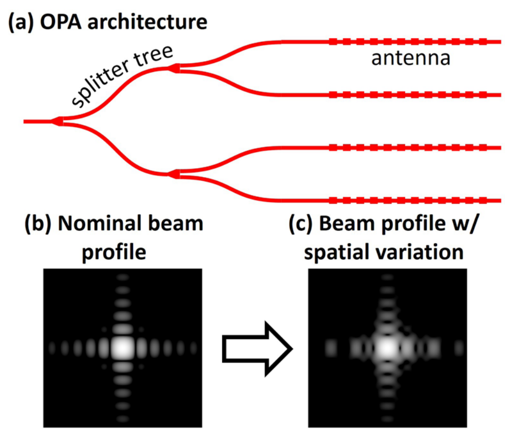
Impact of Spatial Variations on Integrated Optical Phased Arrays

7.06

Z. Zhang, M. Notaros, Z. Gao, U. Chakraborty, J. Notaros, D. S. Boning

Integrated optical phased arrays (OPAs) enable dynamic control of free-space light in a compact form factor and are promising for applications including light detection and ranging (LiDAR) and holographic displays. However, since OPAs are large-scale systems spanning several millimeters and consisting of hundreds or thousands of device components, they can be very susceptible to manufacturing process variations, which significantly impact performance.

In this work, we study the impact of spatially correlated geometric variations on splitter-tree-based OPAs. These variations can arise from deposition and etching processes. We identify the sources of variation and study the effect of different architecture parameters; our numerical analysis is validated through experimental results. These results identify the sources and impacts of fabrication variation and enable more robust OPA designs or fast calibration of active OPAs to achieve good performance given manufacturing limitations.



◀ (a) Simplified top-view schematic of a splitter-tree-based OPA, the simulated 2D intensity distribution of the emitted beam (b) of the nominal case and (c) when applying linewidth spatial variation to the entire OPA.

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Research Interests:
Information processing, Machine Learning for Time Series in Manufacturing.

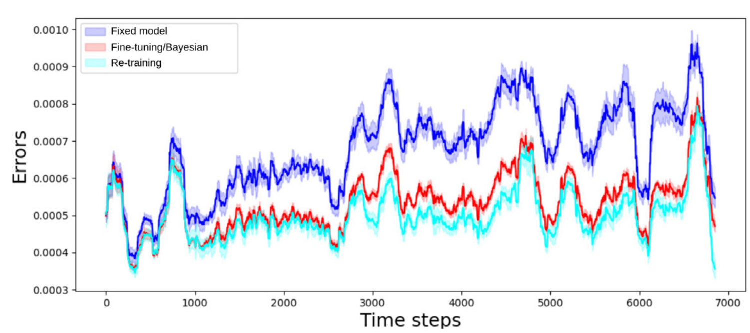
Training Neural Networks under Concept Drift with Bayesian Inference for Time Series Forecasting

7.07

F.-K. Sun, D. S. Boning
Sponsorship: Lam Research, HARTING Technology Group

Time series are used to analyze and model the dynamics of the underlying system for applications such as forecasting and anomaly detection. In many cases, due to wear, tear and environmental changes, the dynamics of the system shift over time. This is known as concept drift. The most straightforward way to deal with concept drift is to re-train the model when new data points have been observed. However, this is time consuming and computationally intensive.

Here, we focus on forecasting, as it is the most common and important tasks. First, we verify that almost all widely-used public time series datasets have the issue of concept drift. We find that fine-tuning the NN alongside new data points allows the NN to adapt to the concept drift with good performance. Finally, we adopt a Bayesian inference approach to more effectively update the NN's belief whenever new data points are available. Our method allows the NN to more effectively learn under concept drift without re-training.



▲ Mean-squared errors on testing set. Fixed model applies the same model as trained on the training set for the testing set. Fine-tuning and Bayeisan models both adapt the model overtime. The re-trained model is considered to be the lower-bound.

Optical Probes of Triplet Exciton Sensitization of Silicon

7.08

N. Wong, C. F. Perkinson, A. Q. Wu, W. A. Tisdale, M. G. Bawendi, M. A. Baldo

Sponsorship: US Department of Energy

With the climate changing, solar power is a major contender as a renewable energy resource. To match the growing global energy demand while meeting space and cost limitations, efficiencies of solar cells need to improve. However, the efficiencies of crystalline silicon solar cells, the current industry standard, are approaching the maximum theoretical limit. One method of going beyond this limit is to sensitize the silicon (Si) by using a material that can perform singlet exciton fission (SF), a carrier multiplication process that can create two triplet excitons (electron-hole pairs) from a single photon. Successful transfer of these two triplet excitons to silicon can result in increased photocurrent and improved efficiencies.

Recent work has shown coupling between Si and the archetype SF material tetracene (Tc) in the presence of passivating interfacial layers of Hafnium oxynitride. Excitation spectra show a boost in the photoluminescence from Si when Tc is photoexcited that may be caused by energy transfer or changes in the silicon passivation . To experimentally distinguish between these phenomena and understand the complex dynamics of excited states and charges at silicon/SF interfaces, we have developed a spectroscopy technique that is robust to the weak and intensity-dependent photoluminescence from silicon. Using combinations of biasing optical pumps and selective modulation of SF rates using a magnetic field, we study structural variations at the interface to probe the mechanism of coupling at Hafnium oxynitride interfaces and other rationally-designed heterostructures. We demonstrate positive contributions from tetracene to silicon photoluminescence that suggest a key role for charge transfer states in realizing solar cell efficiency enhancements from singlet exciton fission. These results can help identify important material parameters for enhancing silicon solar cell efficiencies beyond the theoretical limit.

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Research Interests:
Electronic devices, Electronics, Energy, Energy harvesting devices & systems, Lasers, Light-emitting diodes, Molecular & polymeric materials, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics, Organic materials, Photonics, Photovoltaics, Si, Spintronics.

Flexible Wafer-Scale Silicon-Photonics Fabrication Platform

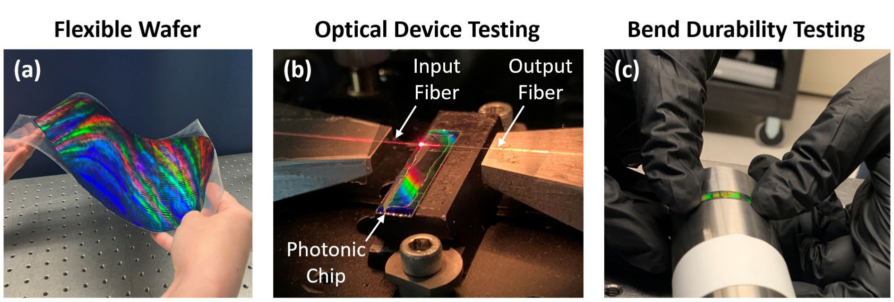
7.09

M. Notaros, T. Dyer, A. Hattori, K. Fealey, S. Kruger, J. Notaros

Sponsorship: Defense Advanced Research Projects Agency (DARPA) VIPER program (Grant No. FA8650-17-1-7713)

The field of silicon photonics has advanced rapidly, enabled by advanced wafer-scale platforms and fabrication processes. However, these processes have been focused on fabrication on silicon substrates that result in rigid photonic wafers and chips, which restrict the possible application areas. There are many applications that would benefit from flexible photonic solutions, such as wearable healthcare monitors and pliable displays. However, prior demonstrations of flexible optical devices have been limited to die-scale fabrication, which is not easily scalable.

To address the need for scalable flexible photonics, in this work, we develop a wafer-scale CMOS-compatible platform and fabrication process that results in 300-mm-diameter flexible wafers. We experimentally demonstrate key functionality, including waveguide routing, passive devices, and bend durability. This work enables silicon photonics to delve into expanded applications, including healthcare monitors and pliable displays.



▲ Photographs of (a) a fabricated flexible silicon-photonics wafer, (b) a flexible photonic chip on the experimental setup, and (c) a flexible photonic chip undergoing bend durability testing.

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Electronic devices, Electronics, III-Vs, Integrated circuits, Lasers, Light-emitting diodes, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Si.

Silicon Photonics for Chip-Based 3D Printing

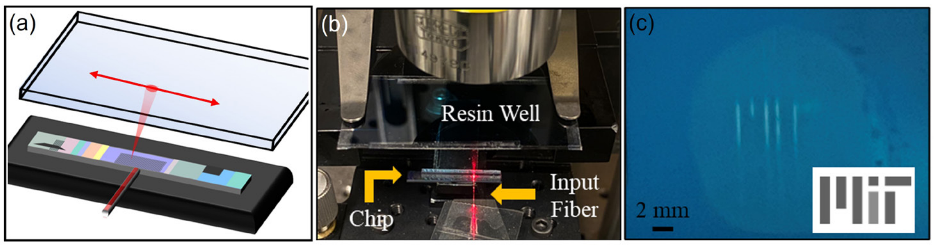
7.10

S. Corsetti, M. Notaros, T. Sneh, A. Stafford, Z. Page, J. Notaros

Sponsorship: MIT Rolf G. Locher Endowed Fellowship, NSF Graduate Research Fellowship

3D printing has facilitated diverse scientific advancements ranging from rapid prosthetic prototyping to forensic sample reconstruction. To maximize build speed while maintaining print quality, modern 3D printers rely on complicated systems for mechanical laser routing and specialized build platforms for strain reduction. The cost and upkeep of these systems, in addition to the UV-light printing standard, have prevented 3D printing from contributing to low-cost and biocompatible applications.

In this work, we develop an on-chip integrated photonic system that enables dynamic non-mechanical control of visible light and controllably cures a visible-light-curable liquid resin. This research takes the first step towards a form of 3D printing that will allow for non-mechanical, volumetric 3D printing with interference patterns generated by a single chip. The complete development of this technology would allow for inexpensive, rapid 3D printing in the biocompatible visible-light regime.



▲ (a) Conceptual diagram showing a photonic chip radiating visible light onto liquid resin, with an arrow to indicate beam-steering. (b) Photograph of the experimental setup and photonic chip. (c) Photograph showing example MIT logo print.

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Research Interests:
Communications, Displays, Electronic devices, Electronics, III-Vs, Integrated circuits, Lasers, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Quantum devices, Sensors, Systems, Transducers.

Underwater Free-Space Optical Communications Using Integrated Optical Phased Arrays

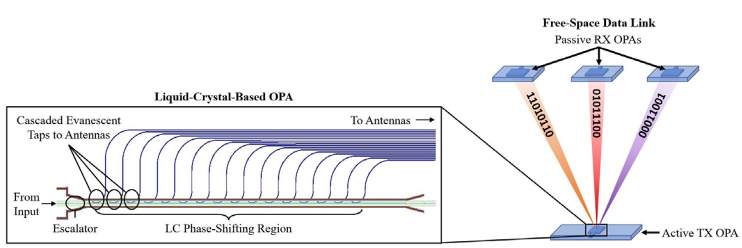
7.11

D. DeSantis, M. Notaros, J. Notaros

Sponsorship: DARPA VIPER program (Grant No. FA8650-17-1-7713), NSF Graduate Research Fellowship (Grant No. 1122374), MIT Rolf G. Locher Fellowship

Optical signals can transmit large quantities of data quickly, which has inspired the historic field of fiber-optic communications. Recently, free-space optical communications links have been demonstrated with infrared integrated optical phased arrays (OPAs) with speeds up to gigabits per second. However, a capability gap exists for underwater communications, where infrared optical links are heavily attenuated and radio-frequency or acoustic links are limited to low bandwidths and high latencies. A promising alternative is operation at visible wavelengths, where water is highly transparent.

In this work, we propose a silicon-photonics-based chip-scale solution to underwater communications that leverages visible-light liquid-crystal-based OPAs to enable electronic steering of high-speed data-modulated optical beams through water with lower loss. Such capabilities enable underwater applications, such as improved submarine communication capabilities and underwater antenna remoting.



▲ Conceptual diagram showing a free-space data link between one transmit and three receive optical phased arrays (OPAs), with a simplified schematic of the integrated visible-light liquid-crystal-based OPA shown in the inset.

Single-Shot Optical Neural Network

7.12

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Sponsorship: NTT Research Inc., NSF EAGER program (CNS-1946976), U.S. ARO (W911NF-18-2-0048), NSERC (PGSD3-517053-2018), NSF GRFP (1745302), Hertz Foundation Elizabeth and Stephen Fantone Family Fellowship, VATAT postdoctoral scholarship for quantum technology

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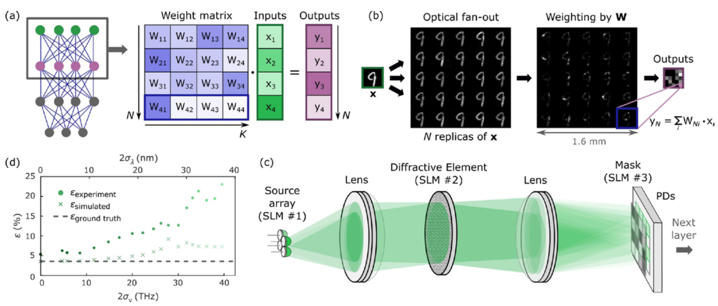
Research Interests:
Lasers, Multimedia, Optoelectronics, Photonics, Artificial intelligence, Neural networks.

Deep neural networks (DNNs) have had transformative impacts in machine learning tasks such as classification. To improve accuracy and solve more complex problems, in recent years, DNN model sizes have grown exponentially. However, larger models increase latency and power consumption due to additional electronic data movement in existing hardware with limited scalability, constraining DNN performance. Here, we experimentally demonstrate an optical neural network (ONN) that computes DNN layer outputs in a single shot, minimizing expensive electronic data movement and lowering multiply-accumulate costs. We classify the MNIST handwritten digit dataset with 95.2% accuracy (ground truth: 96.9%) and determine our system's upper bound to computational throughput (~0.9 exaMAC/s). We show the first large-scale (~1000-input), fully programmable analog ONN that can implement existing DNNs without costly retraining, presenting a path toward high-efficiency DNN computation in data centers.



◄ (a) DNN layer (matrix-vector multiplication or MVM). (b) Single-shot MVM: fan-out of block-encoded x over rows of W with block-wise summation to compute y. (c) Simplified schematic. (d) Measured classification error ε with supercontinuum source with variable bandwidth 2σ.

Session 8: Quantum Technologies

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Emitting and Absorbing a Directional Microwave Photon with Waveguide Quantum Electrodynamics

8.01

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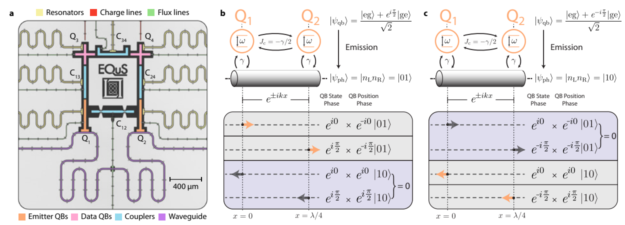
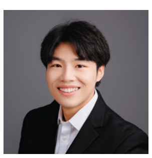
Sponsorship: Amazon Web Services Center for Quantum Computing, Department of Defense, US Army Research Office, Department of Energy Office of Science - National Quantum Information Science

Routing quantum information between non-local computational nodes is a foundation for extensible networks of quantum processors. Propagating photons are efficient carriers of quantum information. In this work, we develop a quantum interconnect composed of an emitter, receiver, and propagation channel. We demonstrate high-fidelity directional microwave photon emission with quantum interference using an artificial molecule comprising two superconducting qubits strongly coupled to a bidirectional waveguide. By emitting time-symmetric photons from one module, we operate another identical module tiled along the waveguide as an absorber of photons, developing an interconnect capable of hosting remote entanglement for extensible quantum networks.



▲ a) A false-colored optical micrograph of the device. b) Schematic outlining the quantum interference effect that enables the emission of a rightward-propagating photon in the waveguide. c) Same as b) but for a leftward-propagating photon.



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Research Interests:
Information processing, Multimedia, Quantum devices, Systems, Computer Architecture, Machine Learning, Quantum Computing.

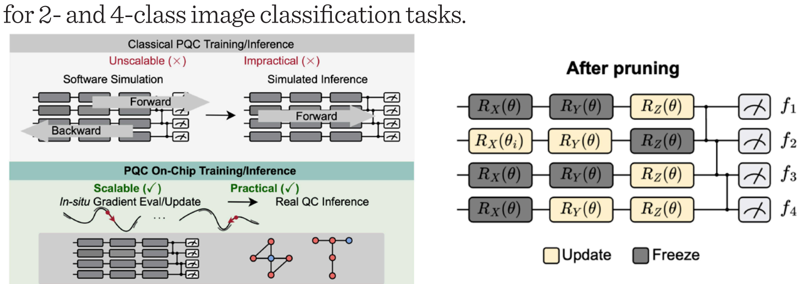
QOC: Quantum On-Chip Training with Parameter Shift and Gradient Pruning

8.03

H. Wang, Z. Li, J. Gu, Y. Ding, D. Z. Pan, S. Han

Sponsorship: MIT-IBM Watson AI Lab, NSF CAREER Award, Qualcomm Innovation Fellowship

Parameterized Quantum Circuits (PQC) is promising to achieve quantum advantage. The scalable training needs to be offloaded to real quantum machines instead of using exponential-cost classical simulators. We present QOC, the first experimental demonstration of practical on-chip PQC training. We find that due to the significant quantum errors (noises) on real machines, gradients obtained from naive parameter shift have low fidelity and thus degrading the training accuracy. To this end, we further propose probabilistic gradient pruning to firstly identify gradients with potentially large errors and then remove them. Specifically, small gradients have larger relative errors than large ones, thus having a higher probability to be pruned. We perform extensive experiments with the Quantum Neural Network (QNN) benchmarks on 5 classification tasks using 5 real quantum machines. The results demonstrate that QOC achieves over 90% and 60% accuracy for 2- and 4-class image classification tasks.



(a) (b)

▲ (a) In QOC, PQC training and inference are both performed on real quantum machines, making the whole pipeline scalable and practical. (b) Gradients are probabilistically pruned with a ratio in the pruning window to mitigate noises and stabilize training.

An End-to-End Photonic Deep Neural Network Processor with Optically-Accelerated Training

8.04

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Sponsorship: National Science Foundation, Air Force Office of Scientific Research, NTT Research

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Research Interests:
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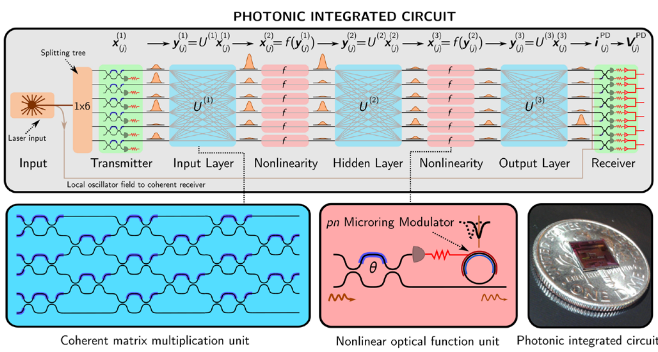
As deep neural networks (DNNs) revolutionize machine learning, energy consumption and throughput have emerged as key limitations of digital electronics. This has motivated the development of novel DNN hardware, such as optical accelerators. However, co-integrating optical linear and nonlinear computing units into a single chip, end-to-end processor has remained an outstanding challenge. Here we report the realization of this goal in an end-to-end photonic DNN processor, fabricated in a commercial CMOS process, that performs DNN inference and training.

Our system, which integrates multiple optical computing units for matrix algebra and nonlinear functions into a single chip, realizes all-optical processing of data in a three-layer DNN. The system latency is less than 500 ps, unlocking new applications that require ultrafast processing of optical signals. Using in situ training, we achieve on-chip accuracies on a vowel classification task identical to those obtained on a digital computer.



◀ System architecture of the end-to-end photonic DNN processor, which computes both matrix algebra and nonlinear functions in the optical domain. Optical inference is computed in a single shot without readout or amplification between DNN layers.

Design and Characterization of 'Soft-firefly' Powered by Electroluminescent Dielectric Elastomer Actuators

8.05

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Sponsorship: Research Laboratory of Electronics, MIT

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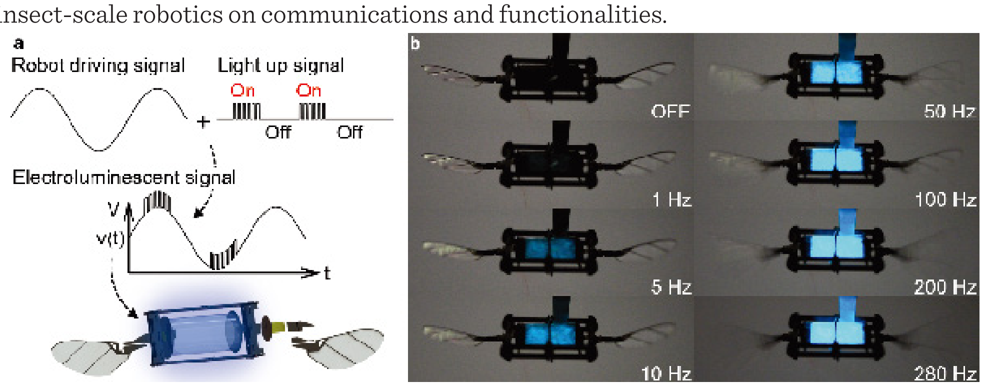
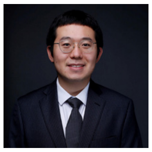
Actuators, Electronics, Nanomaterials, Power Management, Robotics, Sensors, Transducers.

Inspired by the agile movement and high controllability of flying insects, recent works introduced the design of a 'Soft-fly' powered by dielectric elastomer actuators (DEAs). However, in small-scale robots, it is very challenging to embed functionalities due to significant limitations on size and payload. This study addresses this issue by introducing a multi-functional DEA, which can simultaneously actuate, sense, and communicate without additional electrodes or wires.

In this work, we present the fabrication of the multi-functional DEA using electroluminescent particles, and the characterization of the luminance as a function of frequency and electric field. Then, we introduce a signal processing method to drive the robot and to light-up the DEA simultaneously. We also demonstrate the capability of the robot sensing the collisions and responding by blinking the DEA during the operation. The results pave the next stage of insect-scale robotics on communications and functionalities.



▲ (a) Driving signal of 'Soft-firefly' (top) and the assembly structure of the robot with an electroluminescent DEA (bottom). (b) Images that show a robot's electroluminescence intensity at different driving frequencies.



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Research Interests:
2D materials, Artificial Intelligence, Displays, Electronic devices, Electronics, Field-Emitter devices, Integrated circuits, Light-emitting diodes, Nanomanufacturing, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Quantum device.

The Effect of Starting Materials on the Synthesis of Janus Monolayer Transition Metal Dichalcogenides by Atomic-Layer Substitution

8.06

T. Zhang, K. Xie, Z. Yu, K. Zhang, A.-Y. Lu, H. Liu, J.-H. Park, X. Ji, X. Zhang, S.-Y. Tang, X. Zheng, N. Mao, J. Wang, L. Zhou, S. Huang, M. Terrones, Y. Guo, 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 (TMDs) are a unique type of two-dimensional (2D) materials with strong out-of-plane asymmetry and built-in electric dipole, which are promising candidates for applications such as piezoelectrics, catalysis, and spintronics. The room-temperature (RT) synthesis and patterning of Janus TMDs have recently been realized through a plasma-assisted atomic-layer substitution (ALS) approach, and this method steers the reaction pathway in a diverse energy landscape compared to the high-temperature conversion process. For the synthesis of MSSe-type Janus TMDs (M = Mo, W, etc.), the RT-ALS process can start either from MS_2 or MSe_2. In this work we presented a detailed comparison of the conversion yield and material quality of Janus MSSe monolayers converted from MS_2 and MSe_2 prepared by different methods, and found that the choice of starting materials can affect the efficiency of RT-ALS reactions. Our results clearly indicate that the RT-ALS process is more efficient for the conversion of MSe_2 to MSeS, when compared to that of MS2 to MSSe. Density functional theory (DFT) calculations further reveal that the reaction energy barrier and the overall reaction energy for synthesizing MSSe (MSeTe) are lower when MSe_2 (MTe_2) is used as the starting material, aligning well with our experimental findings. These results improve the understanding of the RT-ALS conversion process for the synthesis of Janus TMDs, and may provide useful guidance in the future for designing optimum RT-ALS pathways to obtain various Janus 2D materials with high yield and enhanced uniformity.

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Research Interests:
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Frequency Multiplexing of Cryogenic Sensors for the Ricochet Experiment

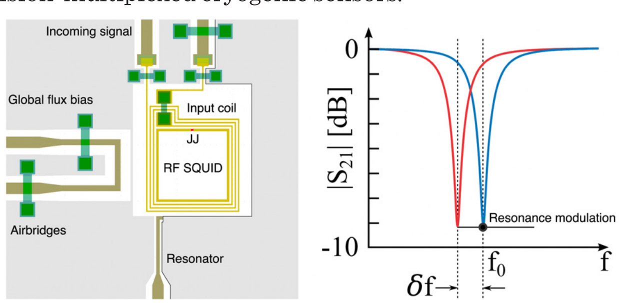
8.07

W. Van De Pontseele, J. Yang, P. Harrington, S. Weber, S. Henderson, W. Oliver, J. Formaggio
Sponsorship: DOE QuantISED award DE-SC0020181, Heising-Simons Foundation

Readout of weak microwave signals over a wide bandwidth is increasingly important for fundamental science. The high frequency allows multiplexing detectors and reduces low-frequency noise for experiments such as Ricochet.

Ricochet aims to measure coherent neutrino scattering to search for new physics. It consists of superconducting crystals that function as bolometers and are read out using transition-edge sensors.

We designed and characterised devices for frequency multiplexing in 6 and 18-channel configurations with Lincoln Laboratory. The signals inductively couple into RF SQUIDS that modulate the resonant frequency of aluminium resonators. These high-Q resonators connect to a common RF feedline, reducing cabling and heat loads. The low-frequency signals are recovered using SLAC Microresonator Radio Frequency (SMuRF) electronics for read out of frequency-division-multiplexed cryogenic sensors.



▲ Schematic of a single RF SQUID of the 18-resonator chip. The scale of the inner SQUID loop is 60x60 micron. Fabricated at Lincoln Laboratories using Al-AlOx-Al trilayer process. (right) Effect of an incoming current on the resonant frequency.

Integrated Photonics for Advanced Cooling of Trapped-Ion Quantum Systems

8.08

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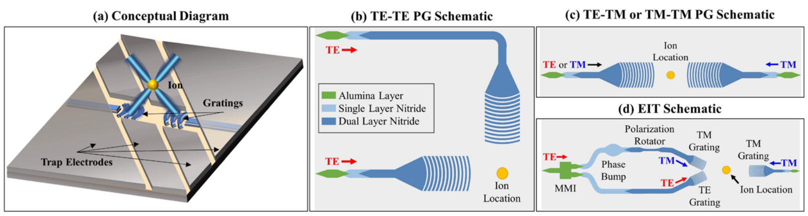
Sponsorship: NSF QLCI HQAN (2016136), NSF QLCI Q-SEnSE (2016244), MIT CQE (H98230-19-C-0292), NSF GRFP (Grant No. 1122374), MIT Cronin Fellowship, MIT Locher Fellowship

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 integrated-photonics-based system architectures and design key integrated devices for two advanced cooling schemes, polarization gradient and electromagnetically-induced-transparency. This improves cooling performance for trapped ions, enabling scalable quantum systems.



▲ (a) Conceptual diagram of the integrated PG-cooling system. Simplified schematics showing the proposed integrated-photonics-based architectures for (b) TE-TE PG cooling, (c) TE-TM or TM-TM PG cooling, and (d) EIT cooling (not to scale).

Machine-learning-assisted Analysis for the Correlation Between Growth Parameters of Hexagonal Boron Nitride

8.09

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Research Interests:
2D materials, Biological devices & systems, Electronic devices, Electronics, Field-Emitter devices, III-Vs, Integrated circuits, MEMS & NEMS, Nanomaterials, Nanotechnology, Optoelectronics, Photonics, Quantum devices, Spintronics, Thermal structures, devices & systems.

J.-H. Park, A.-Y. Lu, J. Kong

Sponsorship: ARO MIT-ISN, ARO MURI

Two-dimensional (2D) materials are promising candidates for future electronics due to their excellent electrical and photonic properties. Among all the synthesis approaches, chemical vapor deposition (CVD) is the most extensively used method for synthesizing the large-area and high-quality 2D materials, which can be adopted in industrial application. Wafer-scale monolayer 2D materials have been realized by epitaxial CVD in recent years. For better manufacture and industrialization of 2D materials, a systematic analysis of how the growth dynamics depend on the growth parameters is essential to unravel the growth mechanisms. However, the studies of CVD-grown 2D materials mostly adopted the control variate method and considered each parameter as an independent variable, which is not comprehensive for 2D materials growth optimization. In this work, we synthesized a representative 2D material, monolayer hexagonal boron nitride (hBN), on single-crystalline Cu (111) by epitaxial chemical vapor deposition and varied the growth parameters to regulate the hBN domain sizes. Furthermore, we explored the correlation between two growth parameters and provided the growth windows for large flake size by the Gaussian process. This new analysis approach based on machine learning provides a more comprehensive understanding of the growth mechanism for 2D materials.

Control of Quantum Dot Emission Using Plasmonic Nanoparticle Lattices

8.10

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Sponsorship: Samsung Electronics

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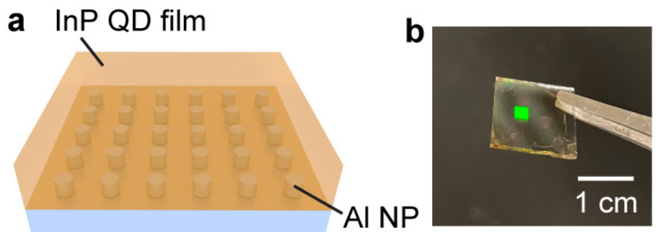
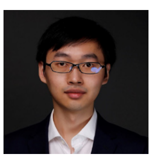
Colloidal quantum dots (QDs) are promising materials for next-generation display technologies because of their high photoluminescence quantum yields, tunable emission colors, and solution processibility. To engineer emission characteristics of QDs, plasmonic lattice structures can provide subwavelength light confinement and suppress radiative loss. In this work, we investigate the coupling of indium phosphide QDs with aluminum nanoparticle lattices to achieve controlled light-emitting properties. We found that conformal coating of QD films on plasmonic lattices can result in hybrid waveguide-lattice modes. By varying the lattice periodicity or the thickness of the QD film, the QD emission wavelength and intensity can be manipulated. Our studies of QD-plasmon interactions open prospects for commercial QD laser devices and quantum-optical technologies.



▲ (a) Scheme of QD-plasmon devices. (b) Photograph of InP/ZnSe/ZnS QD film spin-coated on Al nanoparticle lattices.



Synthesis and Characterization of NbS_2 Grown by Chemical Vapor Deposition

8.11

X. Zheng, J.-H. Park, J. Wang, T. Zhang, J. Kong

Sponsorship: AFOSR MURI

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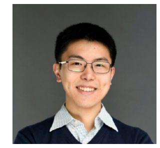
Two-dimensional (2D) materials have attracted significant interest due to their ultra-thin thickness and quantum confinement effect. Currently, significant progress has been made in the growth of various monolayer 2D materials, including the semi-metallic graphene, semiconducting transitional metal dichalcogenides and insulating boron nitride. However, the growth of 2D superconducting materials have been limited. In this project, we investigate the vapor deposition synthesis of monolayer superconducting NbS_2. The structural, optical and electrical properties of as-synthesized NbS_2 will be characterized by optical microscopy, Raman spectroscopy, atomic force microscopy, device fabrication etc. Low temperature studies will also be carried out to explore its characteristics and applications as a charge density wave and superconducting material. Our work demonstrates an industrial applicable approach to controllable growth of 2D NbS_2 for its use in next-generation electronics.

Gradiometric Quarton as a Nonlinear Coupler for Superconducting Qubits and Resonators

8.12

Y. Ye, A. Yen, G. Cunningham, J. Kline, M. Tan, A. Zang, K. Peng, K. O'Brien

Sponsorship: AWS Center for Quantum Computing, MIT Center for Quantum Engineering, Laboratory for Physical Sciences (H98230-19-C-0292), IBM PhD fellowship, NSERC Postgraduate Scholarship



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Research Interests:
Electronic devices, Information processing, Integrated circuits, Photonics, Quantum devices.

Nonlinear couplings between superconducting qubits such as the cross-Kerr interaction are used for important operations including qubit readout and gates. Most nonlinear coupling schemes including the long-established dispersive shift have limited cross-Kerr strength and non-ideal interactions such as residual self-Kerr. We previously proposed quarton couplers as promising nonlinear couplers between qubits and resonators that can facilitate cross-Kerr magnitudes of the order of gigahertz.

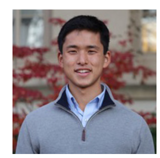
Here, we present a device containing two transmon qubits coupled by a gradiometric quarton coupler. Through flux tuning the gradiometric quarton and transmon SQUID, we explore the potential of purely nonlinear coupling between the qubits and cancellation of qubit self-Kerr to linearize it into a resonator. We present experimental results on a device designed to operate in a parameter space that has large cross-Kerr couplings and large detuning to suppress other unwanted interactions. Large cross-Kerr between qubit and resonator is expected to enable applications including faster high fidelity qubit readout and gates.

Directional Readout Resonator with Interference Purcell Filter for Scalable and Modular Qubit Readout

8.13

A. Yen, Y. Ye, K. Peng, G. Cunningham, J. Wang, K. O'Brien

Sponsorship: NSF Graduate Research Fellowship, MIT-IBM Watson AI Lab



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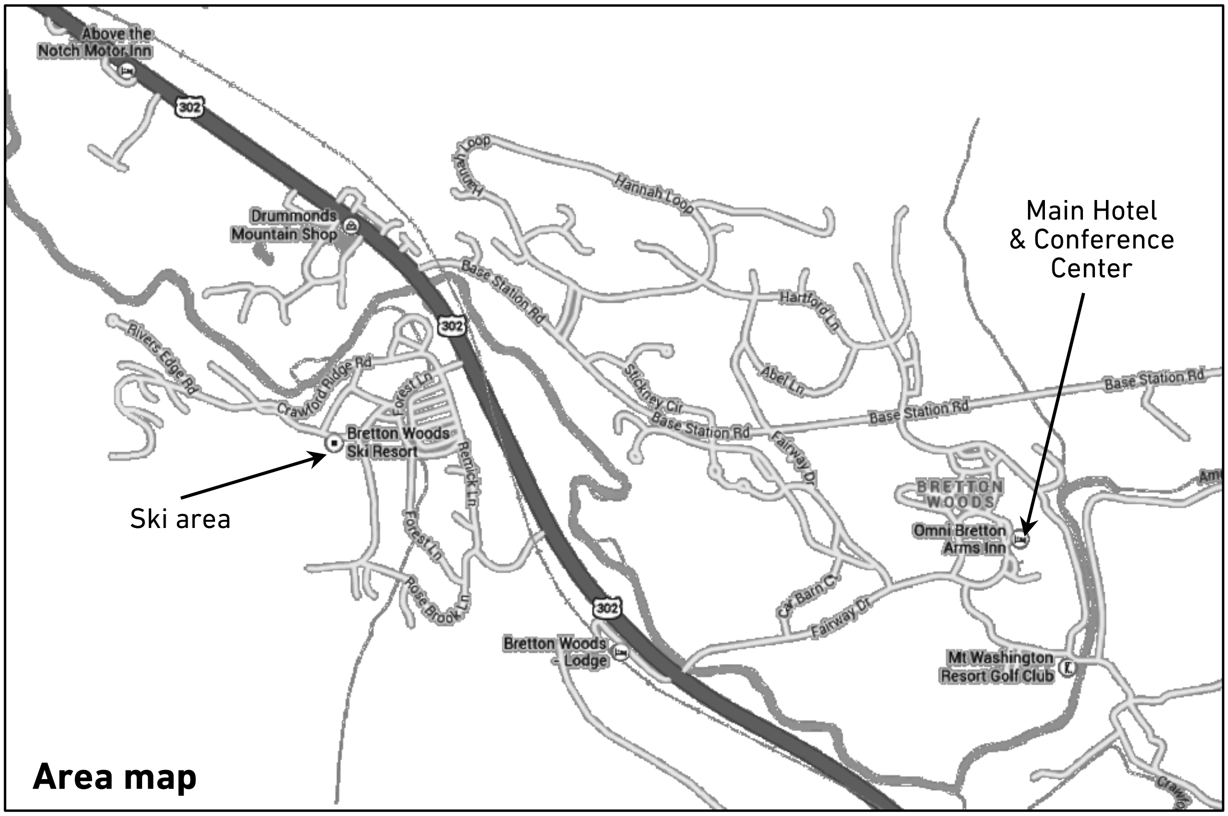
Research Interests:
Artificial Intelligence, Electronics, Information processing, Integrated circuits, Machine Learning, Quantum devices.

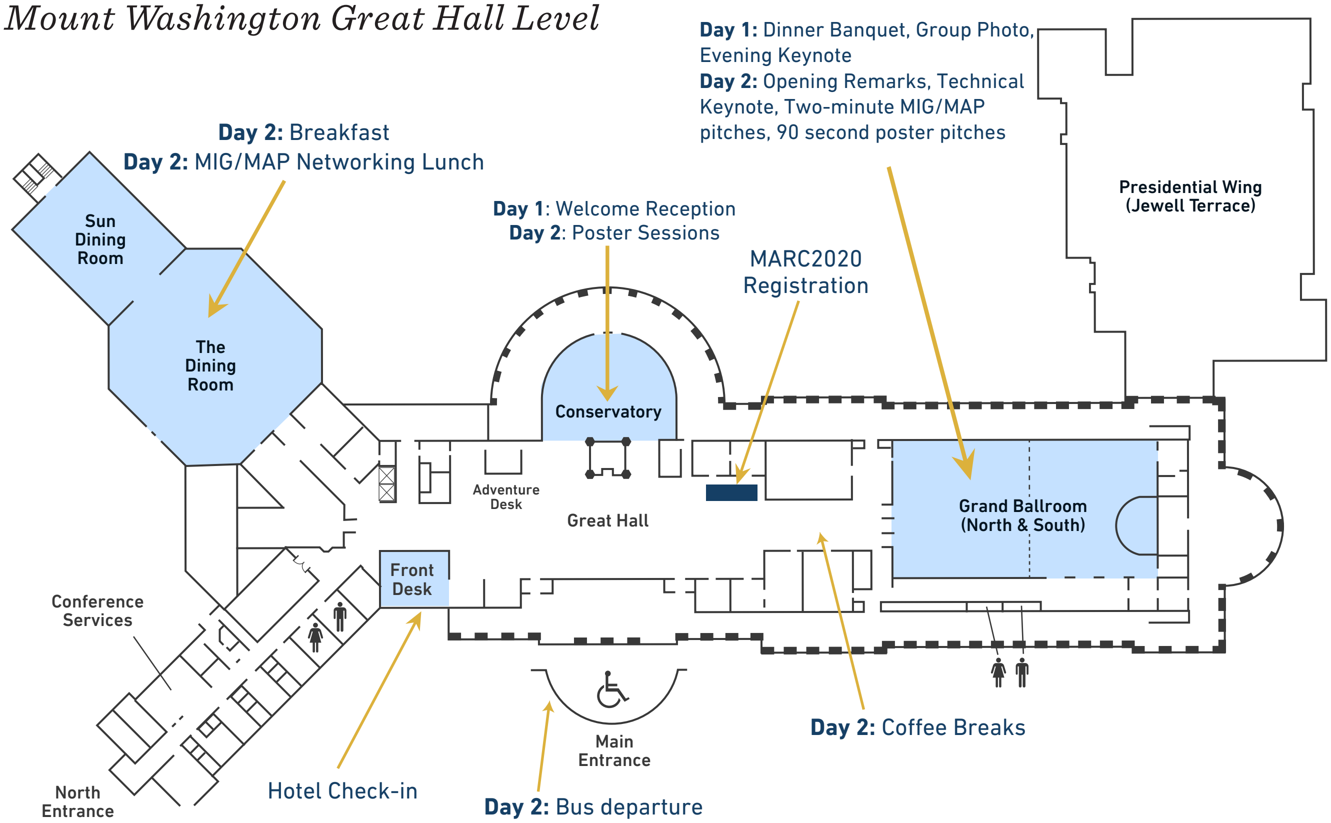
In transmission-based readout of superconducting qubits, a weakly-coupled port is often used at the input of the readout bus to provide directionality close to unity for the readout microwave signal. However, this weakly-coupled port often requires the addition of large and high-magnetic field circulators and isolators for impedance matching, posing a significant challenge to quantum error correction, for which the number of qubits is expected to scale to thousands to millions. Moreover, the weakly-coupled port creates spatial dependence of the couplings to the readout resonators and limits the modularity of typical qubit readout design. In this work, we present a design for "directional readout", which avoids using a weakly-coupled port while preserving near-unity directionality. We also include in our design an "interference Purcell filter," a new form of bandstop Purcell suppression compatible with directional readout. We present progress towards an experimental implementation of directional readout designed to have near-unity directionality and high-fidelity readout of a transmon qubit. This design is expected to facilitate more scalable and modular qubit readout and design.

MAPS

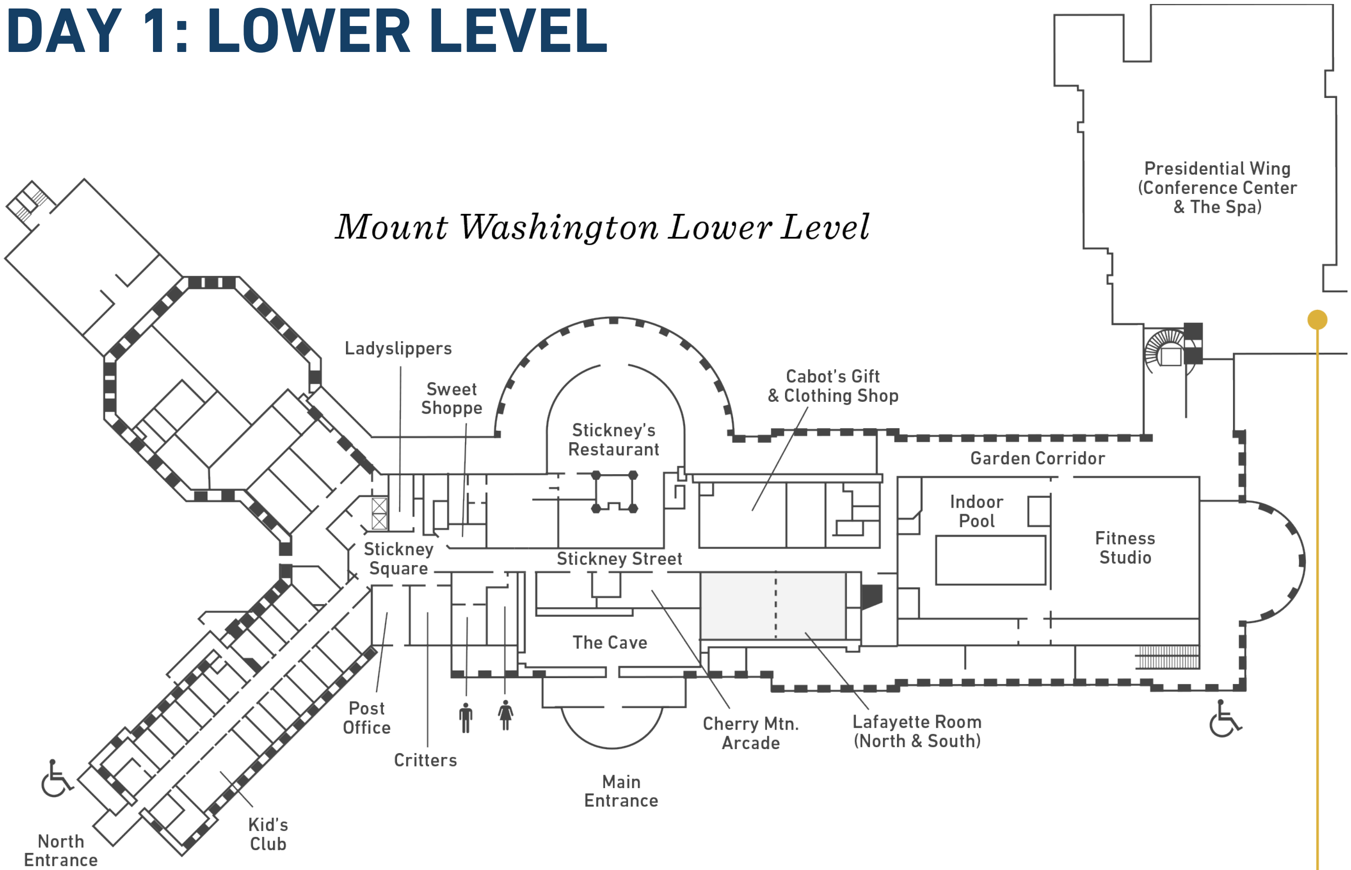


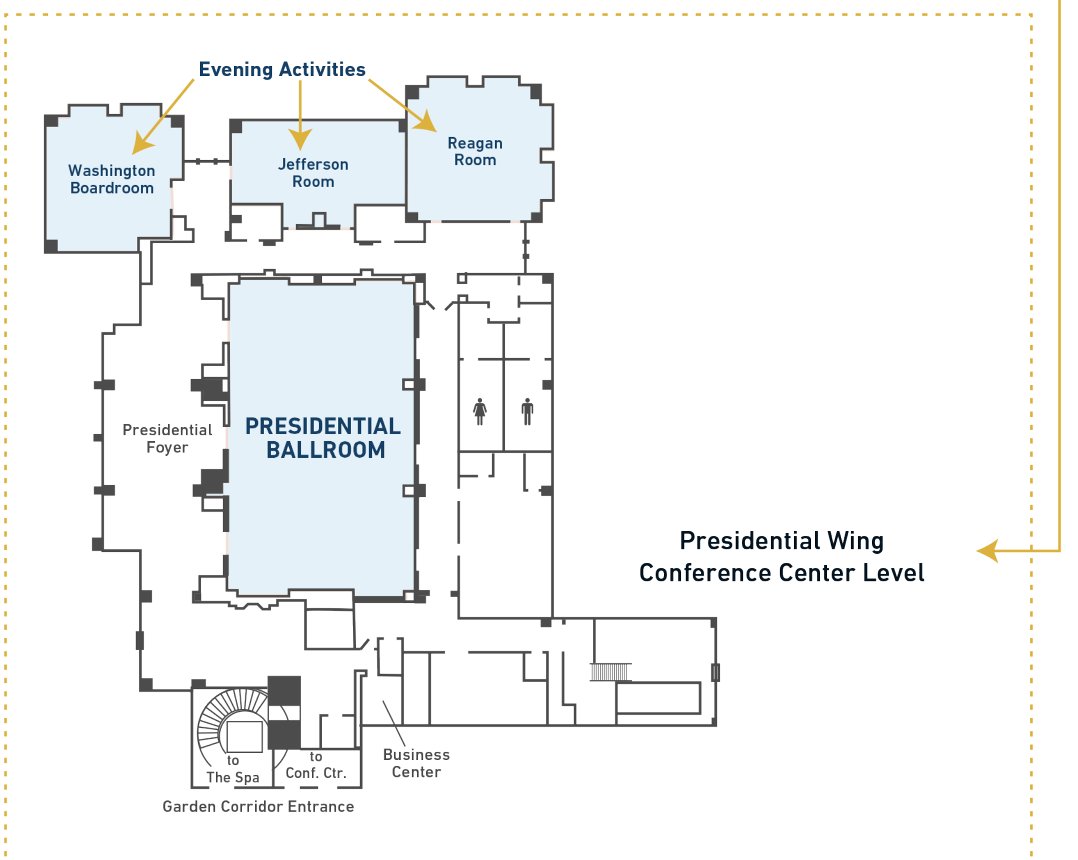
Area map

Mount Washington Great Hall Level



DAY 1: LOWER LEVEL





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