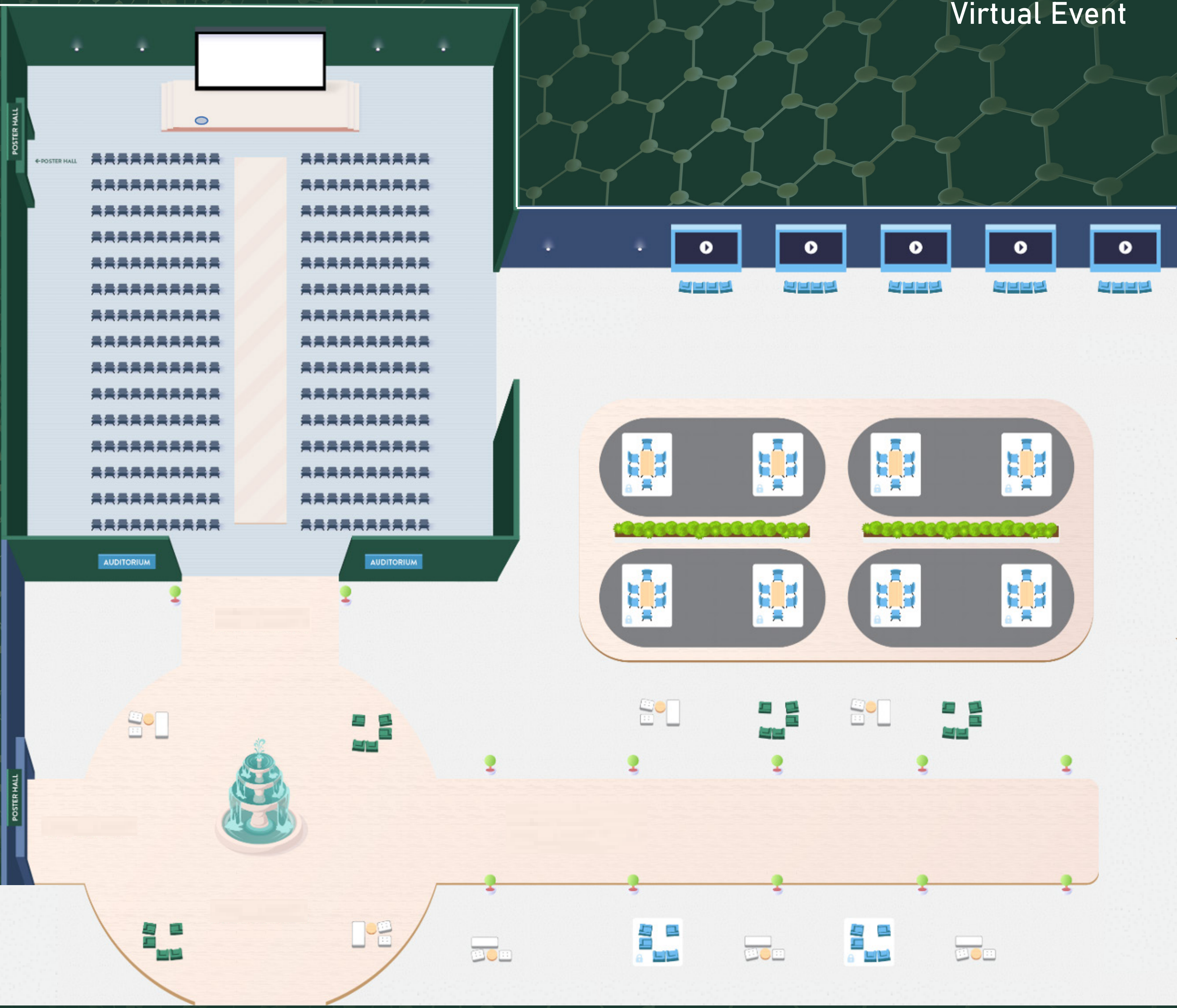
MARC2021:

Microsystems Annual Research Conference

January 26–27, 2021

Virtual Event



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MARC2021

MICROSYSTEMS ANNUAL RESEARCH CONFERENCE

JANUARY 26–27, 2021 • VIRTUAL EVENT

Massachusetts Institute of Technology

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TECHNICAL SESSIONS

COVID-19 Applicable Technologies
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PDF version, January 2021

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INTRODUCTION

Dear colleagues,

First and foremost, welcome to MARC2021! During these unprecedented times, we are grateful to "Gather" with you today and celebrate recent scientific achievements within the MTL and MIT.nano communities.

When we convened for MARC a year ago, our campus, nation, and world were a different place. Since then, we've seen our classrooms cleared, dormitories vacated, laboratories closed, and daily life as we knew it suspended indefinitely. In the months that followed, we witnessed incredible resilience among our community as research continued, classes were reimagined, and each of us created a new normal despite uncertainty and hardship. Of course, most of us have remained lucky throughout the COVID-19 pandemic; our hearts go out to the multitude of lives lost and to those for whom life will never be the same.

The events of the past year have shown us that one of the most precious pillars of an organization is the community it fosters. In recent years, MARC has been held at the Omni Mount Washington Resort in New Hampshire, and its purpose has been as community-oriented as technical. When it became clear that a virtual MARC2021 was our only path forward, our committee was determined to retain the uniqueness and community of MARC at a time when many of us need it most. We're proud to share that many pie-in-the-sky ideas for accomplishing this have since become a reality, all thanks to our student committee, MTL/MIT.nano staff members, and directors of MTL and MIT.nano, Prof. Hae-Seung Lee and Prof. Vladimir Bulović. To this team: we've been blown away by your creativity, fervor, and support, and none of this would have been possible without you.

With that, it is our honor to introduce MARC2021. We are elated to launch our first day with Dr. Irwin Jacobs, the founding chairman and CEO emeritus of Qualcomm and an alumnus of our own. In this fireside chat, Dr. Jacobs will share his riveting career story from earning his graduate degrees at MIT to transforming the wireless telecommunication industry through Qualcomm. Our second day will kick off with a special session titled "COVID-19 Applicable Technologies"; this lightning talk session will showcase technologies applicable to the fight against COVID-19 (or similar threats in the future) being developed in or collaborating with MTL and/or MIT.nano.

MARC2021 will likewise feature 87 student abstracts spanning over 30 research groups. These abstracts will be presented in technical blocks consisting of student research pitches, student poster sessions, and newly-added faculty RAP sessions. And just as importantly, both days will conclude with entertainment and activities including a student-run comedy show, a dessert social, online games, and our traditional MIG/MAP Lunch. We'd like to express our gratitude for the support and presence of our MIG and MAP members, along with each of the abstract authors, participants, and volunteers for these events.

We hope you'll take the opportunity to gather and meet fellow attendees in our virtual conference space on Gather - no social distancing required! We hope our conference packages and provided meals bring tangibility to your experience, especially for those who are far away. And above all, we hope MARC2021 brings you a sense of normalcy and excitement for the future as we come together to celebrate our work and our community.

On behalf of our committee, we wish you an enjoyable MARC2021!

Sincerely,

Jessica Boles and Qingyun Xie
MARC2021 Co-Chairs

AGENDA

DAY 1: JANUARY 26		Gather Platform
12:30 pm - 1:00 pm	**Welcome Reception and Platform Accustomization**	
1:00pm - 1:20pm	**Opening Remarks**	Auditorium*
1:20pm - 2:00pm	**Keynote: Dr. Irwin M. Jacobs** *Founding Chairman and Former CEO of* **Qualcomm**	Auditorium*
2:00pm - 2:10pm	**Break**	
2:10pm - 4:00pm	**Technical Block 1: Integrated Circuits, Energy-Efficiency AI, & Power** 2:10-2:40pm: *60-Sec. Student Pitches* 2:40-3:30pm: *Student Poster Session* 3:30-4:00pm: *Faculty RAP Session: Profs. Ruonan Han, Vivienne Sze, and David Perreault*	 Auditorium* Poster Hall Auditorium*
4:00pm - 4:10pm	**Break**	
4:10pm - 6:00pm	**Technical Block 2: Optics and Photonics, Quantum Technologies, & Biotechnologies** 4:10-4:40pm: 60-*Sec. Student Pitches* 4:40-5:30pm: *Student Poster Session* 5:30-6:00pm: *Faculty RAP Session: Profs. Rajeev Ram, Jelena Notaros, and Kevin O'Brien*	 Auditorium* Poster Hall Auditorium*
6:00pm - 7:00pm	**Break (Dinner)**	
7:00pm - 7:45pm	**MARC Comedy Show**	Auditorium*
7:45pm - 10:00pm	**Dessert Social**	Dining Hall
8:00pm - 10:00pm	**Evening Activities** • *Catan* • *Codenames* • *Among Us* • *Escape The Room*	Game Room*

AGENDA

Day 2: January 27		Gather Platform
9:00am - 9:50am	**Special Session: COVID-19 Applicable Technologies**	Auditorium*
9:50am - 10:00am	**Break**	
10:00am - 11:50am	**Technical Block 3: Electronic Devices, Materials and Manufacturing, & Nanostructures and Nanomaterials**	
	10:00-10:30am: *60-Sec. Student Pitches*	Auditorium*
	10:30-11:20am: *Student Poster Session*	Poster Hall
	11:20-11:50am: *Faculty RAP Session: Profs. Tomas Palacios, Duane Boning, and Jing Kong*	Auditorium*
11:50am - 12:00pm	**Break** *(Order lunch)*	
12:00pm - 12:30pm	**MIG/MAP Pitches**	Auditorium*
12:30pm - 1:30pm	**MIG / MAP Networking Lunch**	Dining Hall
1:30pm - 2:00pm	**Closing Ceremony**	Auditorium*

* Event also accessible via Zoom link.

DAY 1: KEYNOTE

DR. IRWIN M. JACOBS

Founding Chairman and Former CEO

Qualcomm

Dr. Jacobs received his B.S. in electrical engineering from Cornell University in 1956 and his S.M. and Sc.D. degrees in Electrical Engineering from MIT in 1957 and 1959. He was a faculty member in Electrical Engineering at MIT from 1959 to 1966, and a Professor of Computer Science and Engineering at UC San Diego from 1966 to 1972. While at MIT, he coauthored Principles of Communication Engineering, the first textbook on digital communications and information theory.

In 1968, Jacobs co-founded Linkabit Corporation, progressing from consulting services to become a major supplier of digital communication equipment for government and industry. It was selected by ARPA (now DARPA) to develop SATNET to extend the ARPANET to Europe. In 1977, SATNET was one of three networks used in the first live demonstration of the Internet protocol. Industry-first products developed and manufactured by Linkabit included the dual-modem satellite terminal for the Air Force, based on what was later named reduced instruction set processing (RISC), the VideoCipher encrypted satellite-to-home TV system initially for HBO and later industry-wide, and the very-small-aperature satellite terminal (VSAT) business communication system initially for Schlumberger but then commercialized and adopted by Walmart, 7-Eleven, and many gasoline stations for credit card transactions. He sold Linkabit to M/A-Com in 1980, remaining as board member and executive vice-president until April 1985.

With six others from Linkabit, he co-founded Qualcomm July 1, 1985, serving as Chairman and CEO until retiring as CEO in 2005 and Chairman in 2008. Under his leadership, Qualcomm pioneered CDMA technology for the cellular industry, first commercially deployed in Hong Kong in 1995 and in South Korea and the United States in 1996. These second generation (2G) networks initially utilized handsets manufactured in San Diego by Qualcomm. Because CDMA supports efficient voice and mobile wideband internet access, it became the underlying technology for all third-generation (3G) cellular networks, serving billions of subscribers. Qualcomm led the industry in the transition to fourth generation (4G) LTE and now is leading the transition to fifth generation (5G). It licenses its technology worldwide and is among the largest suppliers to global manufacturers of integrated circuits for mobile devices.

Jacobs is a member and past chairman of the National Academy of Engineering, a member of the American Academy of Arts and Sciences, the American Philosophical Society, the National Inventors Hall of Fame, and a Fellow of the IEEE, American Association for the Advancement of Science, and the Computer History Museum. From 2006 to 2016, he was Board Chair of the Salk Institute for Biological Studies and for 17 years served on the Advisory Board of the School of Economics and Management at Tsinghua University in Beijing.

Jacobs has received many awards and honors, including the National Medal of Technology (1994), the James Clerk Maxwell Award, the IEEE Alexander Graham Bell Medal Award, the Dorothy I. Height Chair's Award, of the Leadership Council on Civil Rights, the Franklin Institute Bower Award for Business Leadership, the Marconi Prize, the IEEE Medal of Honor, the Carnegie Medal of Philanthropy with his wife Joan, and the IMEC Lifetime of Innovation Award. He is the recipient of 10 honorary doctorates.

Dr. Jacobs and his wife Joan are active philanthropists and founding signers of the Giving Pledge. They have provided major support to the UC San Diego Jacobs School of Engineering, the UCSD Jacobs Medical Center, the Jacobs Technion-Cornell Innovation Institute, the San Diego Symphony, the San Diego Central Library, the Jacobs-Cushman Food Bank, the High Tech High Charter School System, and the Jacobs Institute for Innovation in Education at the University of San Diego. They annually support fellowships and scholarships for students at UCSD, Cornell, MIT, the Technion, and three New Bedford High Schools.

INDUSTRY CONSORTIUM (MIG & MAP)

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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 MARC2021.

ABSTRACTS

SPECIAL SESSION: COVID-19 APPLICABLE TECHNOLOGIES

SESSION 1: INTEGRATED CIRCUITS

SESSION 2: ENERGY-EFFICIENT AI

SESSION 3: POWER

SESSION 4: OPTICS AND PHOTONICS

SESSION 5: QUANTUM TECHNOLOGIES

SESSION 6: BIOTECHNOLOGIES

SESSION 7: ELECTRONIC DEVICES

SESSION 8: MATERIALS AND MANUFACTURING

SESSION 9: NANOSTRUCTURES AND NANOMATERIALS

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Prospective Evaluation of the Transparent, Elastomeric, Adaptable, Long-Lasting (TEAL) Respirator

SS.01

A. J. Wentworth, J. D. Byrne, S. Orguc, J. Sands, S. Maji, C. Tov, S. Babaee, H.-W. Huang, H. Boyce, P. R. Chai, S. Min, C. Li, J. N. Chu, A. Som, S. L. Becker, M. Gala, A. P. Chandrakasan, and G. Traverso

Sponsorship: Prostate Cancer Foundation, MechE, Brigham and Women's Hospital, Mathworks Fellowship, Analog Devices, NIH, National Institute on Drug Abuse, E-ink Corporation, Gilead Sciences, Philips Biosensing, Hans and Mavis Lopater Psychosocial Foundation.

N95 filtering facepiece respirators (FFR) and surgical masks are essential in reducing airborne disease transmission, particularly during the COVID-19 pandemic. However, currently available FFR's and masks have major limitations, including masking facial features, waste, and integrity after decontamination. In a multi-institutional trial, we evaluated a transparent, elastomeric, adaptable, long-lasting (TEAL) respirator to evaluate success of qualitative fit test with user experience and biometric evaluation of temperature, respiratory rate, and fit of respirator using a novel sensor. There was a 100% successful fit test among participants, with feedback demonstrating excellent or good fit (90% of participants), breathability (77.5%), and filter exchange (95%). Biometric testing demonstrated significant differences between exhalation and inhalation pressures among a poorly fitting respirator, well-fitting respirator, and the occlusion of one filter of the respirator. We have designed and evaluated a transparent elastomeric respirator and a novel biometric feedback system that could be implemented in the hospital setting.

▲ Transparent, elastomeric, adaptable, long-lasting (TEAL) respirator injection molded silicone prototype with anodized aluminum nosepiece and elastic straps modeled on a mannequin head, demonstrating visualization of the mouth area.

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Research Interests:
Biological devices & systems, BioMEMS, electronic devices, electronics, energy, energy harvesting devices & systems, III-Vs, integrated circuits, medical devices & systems, MEMS & NEMS, nanotechnology, photonics, photovoltaics, sensors, machine learning.

Electronics for Transparent, Long-Lasting Respirators

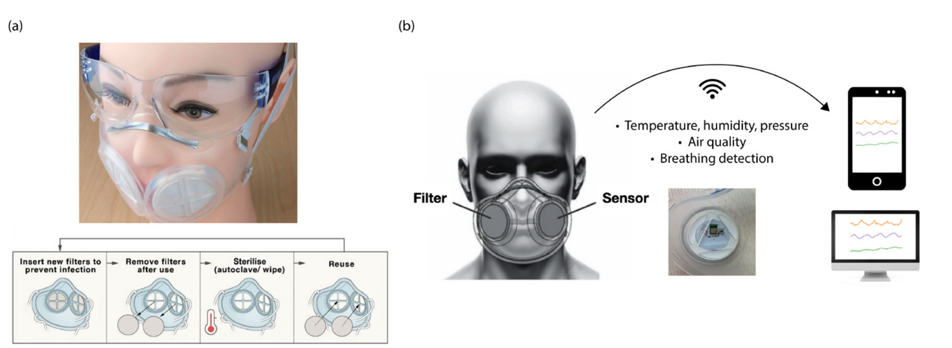
SS.02

S. Orguc, A. Wentworth, J. Byrne, J. Sands, S. Maji, C. Tov, S. Babaee, H. Huang, H. Boyce, P. R. Chai, S. Min, C. Li, J. N. Chu, A. Som, S. L. Becker, M. Gala, A. P. Chandrakasan, G. Traverso

Sponsorship: NIH (5T32DK007191-45)

The use of Personal Protective Equipment (PPE), including the N95 respirators and surgical masks, are essential in reducing airborne disease transmission, particularly during the COVID-19 pandemic. Unfortunately, there has been a shortage of PPE since the beginning of the pandemic. Also, available N95 masks have major limitations, including masking facial features, waste, and integrity after decontamination, forcing researchers to find alternatives.

This work presents a transparent, elastomeric, adaptable, long-lasting respirator with an integrated biometric interface. The mask is mostly made out of silicon rubber and comes with two replaceable filter cartridges. The electronic interface uses one of the filter insert locations to measure temperature, humidity, pressure, and air quality. The system uses BLE and sends real-time sensor data to a phone or a computer. The data can be used to inform the user regarding mask fit, fatigue, mask condition, and potential diagnostic information.



▲ (a) The respirator prototype. (b) System overview for the biometric sensor interface and the wireless operation.

Rapid Monitoring of Sepsis Using Microfluids

SS.03

D. Lee, H. Jeon, B. Jundi, R. M. Baron, B. D. Levy, J. Han, J. Voldman

Sponsorship: NIH U24-AI118656

Sepsis is the dysregulated response to infection, and a major health burden worldwide. Septic patients are commonly monitored by clinical criteria and peripheral blood leukocyte counts; however, monitoring leukocyte counts does not reliably reflect patients' clinical and treatment responses. A major need, therefore, is the development of a device that can rapidly and reliably measure the functional state of the immune system, and in particular the polymorphonuclear neutrophils (PMN) that mediate much of the clinical response. Isodielectric separation (IDS) uses dielectrophoresis (DEP) to determine an electrical signature for PMNs that distinguishes resting from activated cells without any exogenous labels. Here we show the first clinical application of DEP, specifically that electrical phenotyping correlates with clinical severity scores better than leukocyte counts (r = -0.23, not shown), and therefore holds promise for rapid label-free monitoring of sepsis progression. Further, we integrate IDS with a multi-dimensional double spiral (MDDS) inertial separation platform to develop a fully-automated integrated platform for label-free and rapid measurement of PMNs from microliter quantities of human peripheral blood.

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Research Interests:
2D materials, electronic devices, electronics, energy, energy harvesting devices & systems, GaN, III-Vs, light-emitting diodes, nanomanufacturing, nanomaterials, nanotechnology, optoelectronics, spintronics.

A Sample-to-Answer Electrochemical System for Point-of-Care Biomarker Detection

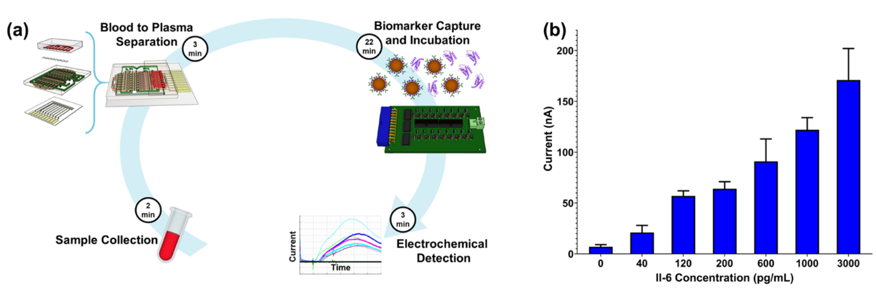
SS.04

K. Kikkeri, D. Wu, J. Voldman

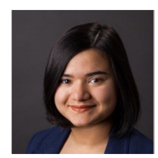
Sponsorship: Novartis Institutes of Biomedical Research, Takeda Fellowship and NSF Graduate Research Fellowship (478969)

The detection of protein biomarkers is a powerful tool for the diagnosis and treatment of various diseases. Typically, the quantification and analysis of biomarkers from blood samples is completed in centralized laboratories through bulky and expensive analyzers. This results in long turnaround times, higher healthcare costs and can be detrimental to patient outcomes.

Here, we present a sample-to-answer Point-of-Care (POC) platform for the rapid detection of protein biomarkers. This POC system integrates on-chip whole blood to plasma separation, bead-based biomarker capture, microfluidic handling and electronic readout into an automated 30-minute assay. We demonstrate the full sample-to-answer workflow through the detection of clinically relevant concentrations of interleukin-6 (IL-6), a marker for the progression of numerous diseases. These results suggest that this POC platform can be used for the sensitive and rapid measure of biomarkers for disease diagnostics and monitoring.



▲ (a) Summary of the sample-to-answer POC workflow. (b) Example detection curve of spiked IL-6 concentrations in blood with corresponding amperometry measurements (n = 5).



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Research Interests:
Artificial intelligence, biological devices & systems, BioMEMS, electronics, machine learning, medical devices & systems, MEMS & NEMS, microfluidic devices & systems, sensors.

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SonicPACT: An Ultrasonic Ranging Method for the Private Automated Contact Tracing (PACT) Protocol

SS.05

M. A. Specter, J. Meklenburg, M. Wentz, H. Balakrishnan, A. P. Chandrakasan, J. Cohn, G. Hatke, L. Ivers, R. Rivest, G. J. Sussman, D. Weitzner

Sponsorship: Defense Advanced Research Projects Agency (Air Force Contract No. FA8702-15-D-0001), MIT-IBM Watson Artificial Intelligence Laboratory, NSF (grant agreement CCF-0939370), Sullivan Family Foundation

Throughout the course of the COVID-19 pandemic, several countries have developed and released contact tracing and exposure notification smartphone apps to help slow the spread of the disease. To allow for privacy preserving contact discovery, Apple and Google have released Exposure Notification Application Programming Interfaces (APIs) to infer device (user) proximity using Bluetooth Low Energy (BLE). Unfortunately, accurately estimating the distance between devices using only BLE signal strength is difficult and prone to errors.

This presentation will describe the SonicPACT, a protocol to use near-ultrasonic acoustic signals on commodity iOS and Android smartphones to estimate inter-device distances. The protocol allows Android and iOS devices to inter-operate, augmenting and improving the current exposure notification APIs. Our initial experimental results are promising, suggesting that SonicPACT should be considered for implementation by Apple and Google.

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Research Interests:
2D materials, electronic devices, medical devices & systems, nanotechnology, sensors.

Highly integrated bioelectronic system based on graphene transistor arrays for multiple ion detection

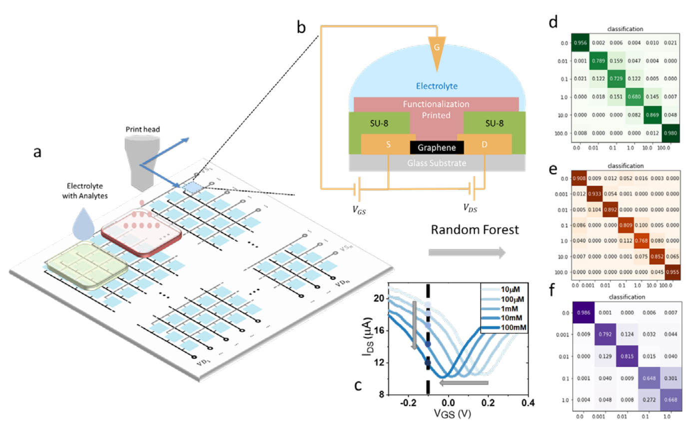
SS.06

M. Xue, C. Mackin, W-H. Weng, J. Zhu, Y. Luo, A-Y. Lu, M. Hempel, E. McVay, J. Kong, T. Palacios

Sponsorship: CIQM NSF (DMR-1231319) and ISN (W911NF-13-D-0001)

High-accuracy, real-time ion sensing is of great interest to the biomedical research and industry, where high throughput bio-related data is critical for accurate disease diagnosis. However, current technology suffers from strong device-to-device variability, reproducibility and reliability. Here, we develop a robust bioelectronic sensing platform made with more than 200 integrated sensing units, custom-built high-speed readout electronics, and machine learning inference for rapid and portable measurement. The platform demonstrates reconfigurable multi-ion electrolyte sensing capability and provides highly sensitive, reversible, and timely response for potassium, sodium, and calcium ions. Leveraging the large dataset and multi-dimensional information collected through the multiplexed sensor array, statistical analysis and machine learning algorithm are applied to enhance ion classification accuracy in complexed mixtures with different ion concentrations.

▶ (a) Schematic of the sensing chip. (b) Schematic of the individual sensing unit. (c) Leftward shifts of I-V curves observed in a typical device with various Na+ ions. (d-f) Cofusion matrix for classification of K+, Na+ and Ca2+ ion in pure solutions



Far UV-C Light-emitting Diode Based on Hexagonal Boron Nitride for High Efficiency Sanitizing

SS.07

J. Zhu, J.-H. Park, M. Xue, Y. Guo, A. Zubair, E. McVay, J. Kong, T. Palacios

Sponsorship: SRC

Deep ultra-violet (UV) light exposure for a certain amount of time and dose is an efficient method to kill most kinds of viruses and sanitize items. Typical UV light-emitting diodes (LEDs) used in these applications are limited to emission wavelengths larger than 270 nm (UV-A and UV-B), which are harmful for human tissues and could cause potential damages to skin and even trigger cancers. Far UV-C light, on the contrary, with a wavelength of ~210 nm can efficiently kill viruses on the human skin, items, and clothes without penetrating the epidermis or causing damage to humans. However, high-efficiency UV-C LEDs have not been demonstrated yet, since they require extremely large band-gap (> 5.6 eV) materials to realize the emission of UV-C light and the corresponded quantum well structure and doping are also difficult to realize.

In this work, we proposed a novel method to fabricate UV-C LED for high efficiency sanitizing based on monolayer hexagonal boron nitride (h-BN), which has a band gap of ~ 5.9 eV and a corresponded wavelength of ~210 nm. By contact work function modulation induced by small molecule dipoles, we realize relatively high carrier injection efficiency with type-II heterojunctions for both electrons and holes, and consequently light-emission. The proposed devices can provide high-efficiency sanitizing for not only fighting the COVID-19 pandemic but also for other applications which require fast disinfection without damaging human tissues, and could pave the way for new surgical equipment.

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CMOS THz-ID: A 1.6-mm^2 Package-Less Cryptographic Identification Tag with 260-GHz Backscatter Communication

1.01

M. I. Ibrahim, M. I. W. Khan, C. S. Juvekar, W. Jung, R. T. Yazicigil, A. P. Chandrakasan, R. Han

Sponsorship: NSF (SpecEES ECCS-1824360)

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Radio-frequency identification (RFID) tags are utilized in a wide range of applications such as tracking, authentication, localization, and supply-chain management. Currently, commercial RFIDs rely on an external antenna to radiate the RF waves. However, this complicates the packaging and increases the size of the tags, limiting their applications with small objects such as medical pills, tooth implants, and semiconductor chips. We demonstrate an ultra-small sub-THz identification tag (THzID) using TSMC 65 nm CMOS process without external components. Our THzID is the smallest reported with far-field communication distance, using 260 GHz backscatter communications, enabled by a 2×2 on-chip patch antenna array. The multi-functional patch antenna receives the downlink signal from the reader. Then the received signal is frequency-shifted and radiated with perpendicular polarization. This configuration enables the beam steering of the backscattered beam for the first time for RF tags, allowing for extra functions such as interrogating many tags using one reader.

The patch antenna also directs the downlink signal to a MOS-based square law detector to demodulate the data from the reader. This demodulated data then feeds a compact elliptic-curve-cryptography (ECC) dedicated processor, which is based on a narrow-strong private identification protocol. The security processor guarantees that any eavesdropper cannot identify which tag participates in the protocol by merely monitoring the wireless link. The THzID consumes a peak power of 21 μW generated by a built-in photovoltaic array, which is placed under the antennas. An on-chip DC-DC converter boosts and regulates the photodiodes output voltage. We demonstrate a measured downlink speed of 100 kb/s and an uplink speed of 2 kb/s across a 5-cm distance from the reader. Our ultra-small, low-cost, and secure THzID empowers a wide range of new applications in manufacturing, logistics, anti-counterfeiting,

One-way Private Key Cryptography with Embedded Spatial Security via Orbital Angular Momentum Waves

1.02

J. Woo, M. I. W. Khan, M. I. Ibrahim, R. T. Yazicigil, A. P. Chandrakasan, R. Han

Sponsorship: NSF

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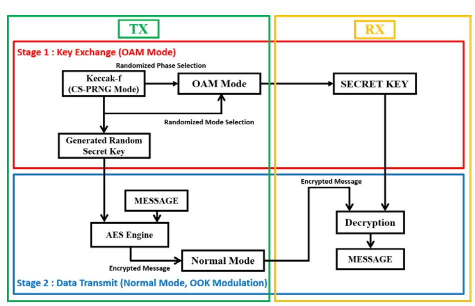
Integrated circuits, cryptographic hardware & security protocols.

As technology progresses and wireless networks have been widely used day to day, securing data in wireless networks has emerged as a major field of research. Conventional bit-level cryptography in higher layers of protocol stack has been studied as a protecting technique of data from an unauthorized party. However, frequent key updating issues or computational overheads make the use of data encryption difficult.

In this work, we leverage the orbital angular momentum (OAM) wave as an additional layer of physical security to be used with data encryption. A trustworthy key distribution mechanism for symmetric cryptography protocol is proposed by exploiting randomly hopping among the orthogonal OAM-wave modes and phases. Keccak block generates randomness for OAM modes, and AES is employed for encryption. This work provides physical-layer security by proposing a low-overhead key distribution mechanism, which is compatible with any higher layer encryption techniques.



▲ Block diagram of proposed architecture.

Simulation and Analysis of GaN CMOS Logic

1.03

J. Jung, N. Chowdhury, Q. Xie, T. Palacios
Sponsorship: MIT EECS - Texas Instruments Undergraduate Research and Innovation Scholar

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Available from June 2021.

Research Interests:
Electronic devices, electronics, energy, GaN, III-Vs, integrated circuits, photovoltaics.

There is an increasing demand for electronics that can operate in high-temperature conditions, such as spacecraft applications and sensors for industrial environments. Electronics based on wide-bandgap materials offer a promising solution, among which gallium nitride (GaN) stands out as a strong candidate due to its excellent material properties and potential for monolithic integration. Most current demonstrations of GaN logic are based on nMOS technology, which has a high static power consumption. Therefore, we are developing GaN CMOS technology, which has lower static power consumption.

This work studies the effect of p-channel transistor and circuit parameters on the performance of CMOS digital logic circuits. We used the MVSG (MIT Virtual Source GaN-FET) model to accurately model the behavior of the n-channel and p-channel transistors, which were fabricated on the developed GaN complementary circuit platform. We simulated and studied several building blocks for digital logic, namely, the logic inverter, multi-stage ring oscillator, and static random-access memory (SRAM) cell, using the developed computer-aided design (CAD) framework. We conducted device-circuit co-design to optimize circuit performance, using a variety of design parameters, including transistor sizing and supply voltage scaling. We projected the high-temperature performance of the circuits through simulations based on experimentally observed device behaviors. The results indicate that GaN CMOS technology based on our monolithically integrated platform has potential for a variety of use cases, including harsh-environment digital computation. We will apply this technique for more complex combinational and sequential logic building blocks, with the eventual goal of realizing a GaN CMOS microprocessor.

1.04

Hardware Trojan Detection using Unsupervised Deep Learning on High Spatial Resolution Magnetic Field Measurements

M. Ashok, M. J. Turner, R. L. Walsworth, E. V. Levine, A. P. Chandrakasan
Sponsorship: NSF Graduate Research Fellowship (1745302) and MITRE Corporation

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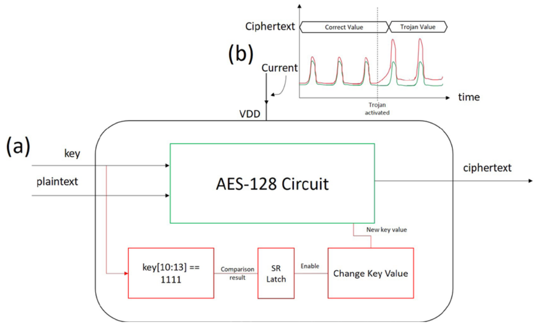
Research Interests:
Electronics, integrated circuits, hardware security.

One major vulnerability of integrated circuits (ICs) is the difficulty of ensuring an IC fabricated in a third-party foundry is not a maliciously modified version of the original design. Such modifications by attackers, called hardware trojans, can leak private data from an IC, change its functionality, or have other effects. Attackers can design trojans so that their effects are not visible during simple functional tests, making detection difficult. However, side channel methods can measure differences in circuit activity resulting from the modified logic to detect trojans prior to the presence of functional changes.

In this work, we achieve a method of detecting small footprint hardware trojans in a FPGA by performing high spatial resolution and wide field of view imaging of the circuit magnetic fields. These are then separated into trojan free and trojan inserted measurements in an automated framework by using an unsupervised convolutional neural network and clustering.



◀ (a) Block diagram of a sample hardware trojan with malicious effects in a cryptographic circuit. ◀ (b) A general method of side channel trojan detection that measures small differences in IC current prior to the trojan payload activation.

SynCells – Heterogeneously Integrated, Wireless Sensor Microsystems

1.05

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Sponsorship: AFOSR

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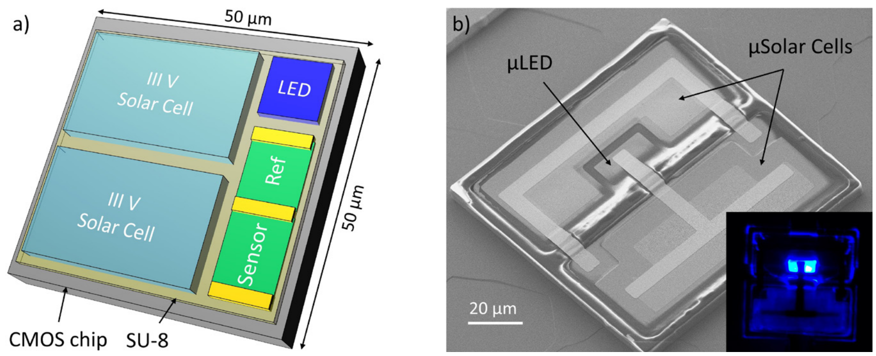
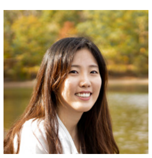
Research Interests:
2D materials, electronics, integrated circuits, nanomanufacturing, nanomaterials, nanotechnology.

Building microsystems as small as biological cells (< 50 µm) is a long-standing engineering dream which could enable new applications from ubiquitous sensing to non-invasive medicine. However, building such system is tricky due to an extremely limited power budget and challenging device integration. Here, we propose SynCells – a 50x50 um sensor microsystem that can detect analytes and wirelessly communicate the sensor data by light. Our SynCells consist of solar cells for energy harvesting, an MoS_2-based chemical sensor and a µLED for communication. All components are heterogeneously integrated on a CMOS chip using SU-8 epoxy, see schematic in Figure a). So far, we have successfully tested all individual building blocks and we verified the feasibility of optical power delivery and communication with a simplified SynCell prototype, as shown in Figure 1 b). In the future, SynCells may be used for sensing in confined spaces, sprayable or printable electronics, and smart composites.



▲ (a) Schematic of SynCell with individual building blocks heterogeneously integrated on a CMOS chip, (b) SEM image a simplified SynCell with solar cells and a µLED. Inset: Image of lit-up µLED under UV light illumination.



Stability Improvement of CMOS Molecular Clocks Using an Auxiliary Loop Based on High-order Detection and Digital Integration

1.06

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Sponsorship: JPL, NSF

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Research Interests:
Integrated circuits.

Recently, chip-scaled molecular clocks (CSMC) have achieved high frequency stability with low power and compact size by using a rotational-mode transition of carbonyl sulfide (OCS) centered around 231.061 GHz as a frequency reference (f0). In the molecular clock, the probing signal generated from the transmitter is frequency-modulated at fm around the center frequency (fc). Since fc is locked to f0 in a feedback loop, the output frequency inherits the excellent stability of the OCS transition frequency.

Due to its fully-electronic implementation, CSMC provided a solution to significantly reduce the cost of high-stability miniaturized clocks. However, the frequency stability is still limited by a finite loop gain of the frequency locked loop (FLL) and detection non-idealities coming from baseline variations which are susceptible to environmental disturbance even though an invariant physical constant is used as the frequency reference. In this work, we propose a new dual loop CSMC architecture based on both fundamental and high-order transition probing as well as digital integration.

In order to achieve a high long-term stability without compromising the SNR, the fundamental harmonic detection forms the main loop, while the higher order probing is used in an auxiliary loop. The loop fine-tunes the PLL's frequency multiplication ratio according to the sign of the high-order detection output. With a proper selection of gain and bandwidth in each loop, the main loop enables the fast correction of frequency and the auxiliary loop responds against long-term frequency variation. Also, the frequency offset between the clock output and the OCS reference can be eliminated when the clock is locked, because the auxiliary loop includes a digital integrator to obtain an infinite DC gain.

As a result, the proposed CSMC combines the advantages of both fundamental locking and high-order locking: high SNR and robustness against the environmental variations.

High Angular Resolution THz Beam Steering Antenna Arrays in 22nm FinFET Technology

1.07

Nathan Monroe

Sponsorship: Intel Corp.

THz Phased arrays are a promising emerging technology for many applications, including THz imaging, radar, communications and other sensing applications. This is largely a result of the smaller wavelength at THz frequencies and accordingly smaller array size and weight. However, challenges exist in their design, particularly the design of THz phase shifters, which are often lossy, power hungry, and physically large, precluding their use in dense arrays. These losses often arise from the high resolution nature of the phase shifters. In addition, lossy on-chip transmission lines significantly degrade system performance. In this work, we apply phased array principles to yield dense THz antenna arrays with only one bit of phase resolution, yielding performance benefits in terms of DC power, THz loss, size, bandwidth and simplicity. In addition, by distributing RF power spatially, many of the losses with RF signal distribution are mitigated. This approach is termed reflectarray (reflector array). We demonstrate our approach on CMOS silicon in the form of a 4x4 mm2 chip containing 7x7 antenna elements, operating at 260GHz. The chip is designed in Intel 22nm FinFET process, and is designed such that multiple chips can be tiled to create large arrays that can be scaled in size based on performance requirements. In addition, we apply similar principles to introduce a true one bit phased array FMCW radar, a monolithic chip radar operating at 260GHz, where the transmit and receive beams can be steered independently. The use of one bit phase shifters comes at a system level performance cost by introducing sidelobes in the radiation pattern. Our work introduces a number of approaches to mitigate this, allowing the one bit phased array design to approach the performance of a phased array with a continuous, analog phase shifter. While still in progress, this work pushes towards practical large-scale THz phased arrays.

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Session 2: Energy-Efficient AI

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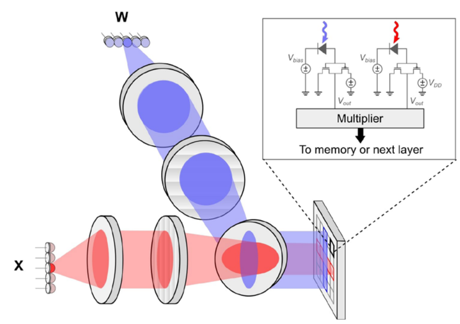
Communications, information processing, integrated circuits, MEMS & NEMS, nanotechnology, optoelectronics, photonics, SI.

Digital Optical Neural Network - Freely Scalable and Reconfigurable Optical Hardware for Deep Learning

2.01

Sponsorship: NSF Graduate Research Fellowship

As deep neural network (DNN) models grow ever-larger, they can achieve higher accuracy and solve more complex problems. This trend has been enabled by an increase in available compute power; however, efforts to continue to scale electronic processors are impeded by the costs of communication, thermal management, power delivery and clocking. We propose a digital optical neural network (DONN) with intralayer optical interconnects and reconfigurable input values. The near path-length-independence of optical energy consumption enables information locality between a transmitter and arbitrarily arranged receivers, which allows greater flexibility in architecture design to circumvent scaling limitations. We analyze the energy consumption of the DONN and find that optical data transfer is beneficial over electronics when the spacing of computational units is on the order of >10µm. As a result, digital electronic systems can be designed which freely scale because of optical length independence.



▲ Possible implementation of digital optical neural network. (a) Free-space computation using diffractive optical elements and beam splitters to multicast vectors onto a photodetector array. (b) Photodetection circuit using receiverless operation.

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Research Interests:
Machine learning, deep learning, autoML.

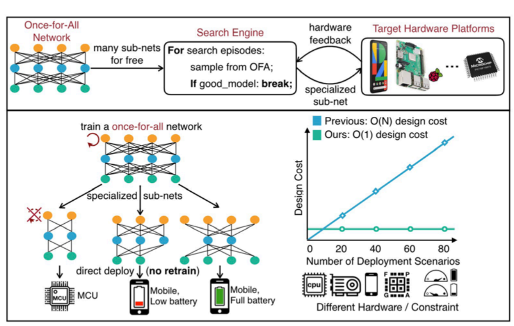
Once-for-All: Train One Network and Specialize it for Efficient Deployment

2.02

H. Cai, C. Gan, T. Wang, Z. Zhang, S. Han

Sponsorship: NSF Career Award #1943349, MIT-IBM Watson AI Lab, Google-Daydream Research Award, Samsung, Intel, Xilinx, SONY, AWS Machine Learning Research Award

We address the challenging problem of efficient DNN inference across many devices and resource constraints. Previous methods either manually design or use neural architecture search (NAS) to find a specialized model and train it from scratch for each case, which is computationally prohibitive. In this work, we propose to train a once-for-all (OFA) network that supports diverse architectural settings by decoupling training and search. We can quickly get a specialized sub-network by selecting from the OFA network without additional training. To efficiently train OFA networks, we also propose a novel progressive shrinking algorithm, a generalized pruning method that reduces the model size across many more dimensions than pruning. It can obtain a large number of sub-networks without losing accuracy. In summary, OFA provides an efficient way to get arbitrary pre-trained neural networks in the design space, which enables fast neural architecture search and neural-hardware co-design.



◀ We train a single OFA network that supports all possible architecture settings in the design space. We can then get many different sub-nets by activating different parts of the OFA network. This approach reduces the total cost from O(N) to O(1).

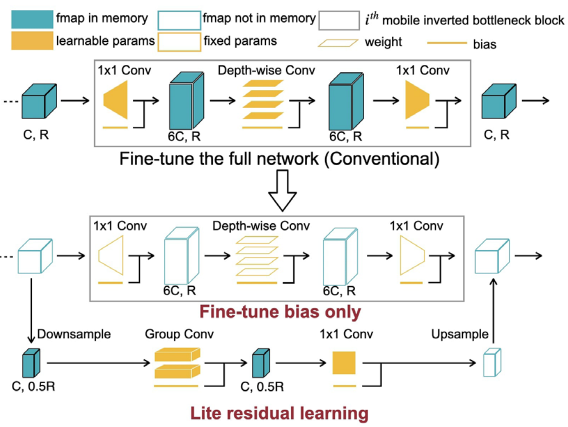
TinyTL: Reduce Memory, Not Parameters for Efficient On-Device Learning

2.03

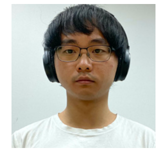
H. Cai , C. Gan , L. Zhu , S. Han

Sponsorship: MIT-IBM Watson AI Lab, NSF CAREER Award #1943349 and NSF Award #2028888

Secure AI systems need to continually adapt to newly collected data on edge devices without leaking them to the cloud. This requires a small memory footprint at training time to fit the tight memory constraint. Existing work solves this problem by reducing the number of trainable parameters. However, this does not directly translate to memory saving since the major bottleneck is the activations, not parameters. In this work, we present Tiny-Transfer-Learning (TinyTL) for memory-efficient on-device learning. TinyTL freezes the weights while only learns the memory-efficient bias modules, thus no need to store the intermediate activations. To maintain the adaptation capacity, we introduce a new memory-efficient bias module, the lite residual module, to refine the feature extractor. Extensive experiments show that TinyTL significantly saves the memory with little accuracy loss compared to fine-tuning the full network.



◀ TinyTL freezes weights and only fine-tunes biases, thus does not need to store intermediate activations. TinyTL further adds memory-efficient lite residual modules to compensate for the capacity loss while incurring little memory overhead.



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SpAtten: Efficient Sparse Attention Architecture with Cascade Token and Head Pruning

2.04

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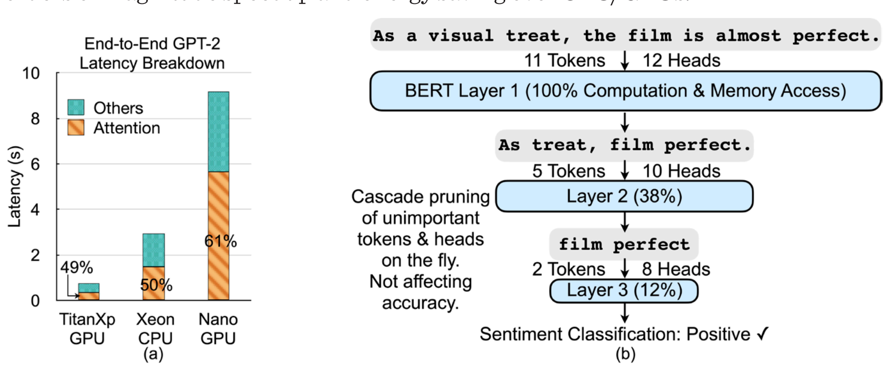
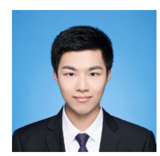
Sponsorship: MIT-IBM Watson AI Lab, NSF CAREER Award, and DARPA SDH

Attention is ubiquitous in Natural Language Processing thanks to its ability to model relationships between tokens. However, CPU/GPUs are inefficient for attention due to its complicated data movement and low arithmetic intensity. Moreover, existing accelerators cannot support attention. We present SpAtten, an algorithm-architecture co-design that leverages sparsity and quantization opportunities to reduce computation and memory access. Inspired by the high redundancy of human languages, we propose cascade token/head pruning to remove unimportant tokens/heads on-the-fly. To support it on hardware, we design a high-throughput top-k engine to rank token/head importance. Furthermore, we propose progressive quantization that first fetches Most Significant Bits and computes, and only fetches Least Significant Bits for low-confidence inputs, trading computation for memory reduction. SpAtten reduces DRAM access by 11.5× with 2 to 3 orders of magnitude speedup and energy saving over CPU/GPUs.



▲ Attention is the bottleneck of NLP models on CPUs/GPUs, and (b) Proposed cascade token and head pruning can significantly reduce computation and memory access with no accuracy loss.



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AI for Microsystems Design

2.05

H. Akay, J. Gammack, S.-G. Kim

Sponsorship: NSF LEAP-HI (1854833)

The applications of microsystems research are broad, but decades of research in the field have resulted in a rich history of documented device and process designs, so large that it is infeasible for an individual human microsystems designer to become familiar with the totality of these published discoveries. The design and fabrication of microsystems is a complex process with many requirements to satisfy, where long lead times and high costs of fabrication result in a high value of implementing a rigorous design process prior to fabrication. The ability to synthesize and characterize thousands of long-form design documents may aid in expediting the knowledge acquisition of microsystems researchers and designers. Recently, methods in machine learning and specifically natural language processing (NLP) have demonstrated competency in extractive reading tasks which can be leveraged, together with a corpus of microsystems documentation, to improve the practice of microsystems designers. Long-form design texts may be extractively mapped from a functional perspective such that the designer can efficiently build on past design successes and learn from the limitations documented by previous efforts. This research outlines a detailed framework for applying NLP models to enhance the practice of designers of micro- and nanoscale devices.

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Research Interests:
Multimedia, systems, machine learning, computer vision.

MCUNet: Tiny Deep Learning on IoT Devices

2.06

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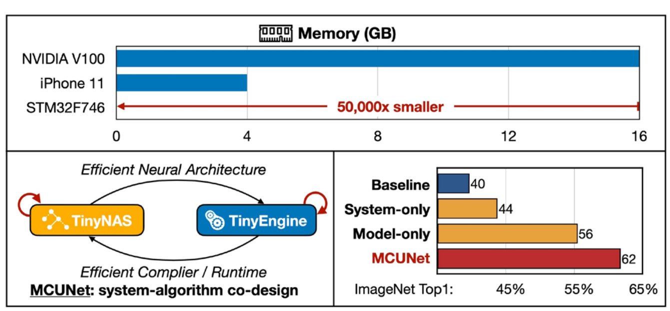
Sponsorship: MIT Satori, MIT-IBM Watson AI Lab, Qualcomm, NSF CAREER, NSF RAPID Award

Machine learning on tiny microcontroller units (MCU) is appealing due to its low-cost and low-power nature. But the memory of MCU is 2-3 orders of magnitude smaller even than mobile phones. We propose MCUNet, a framework that jointly designs the efficient neural architecture (TinyNAS) and the light-weight inference engine (TinyEngine), enabling ImageNet-scale inference on MCUs. TinyNAS adopts a two-stage neural architecture search approach that first optimizes the search space to fit the resource constraints, then specializes the network architecture in the optimized space. TinyNAS is co-designed with TinyEngine, a memory-efficient inference library to expand the search space and fit a larger model. MCUNet is the first to achieve >70% ImageNet top1 accuracy on a commercial MCU. On wake word datasets, MCUNet achieves state-of-the-art accuracy and runs 2.4-3.4× faster with 3.7-4.1× smaller peak SRAM. Our study suggests that the era of tiny machine learning on IoT devices has arrived.



▲ (1) TinyML on MCUs is difficult due to limited memory; (2) MCUNet co-designs the efficient neural architecture (TinyNAS) and efficient compiler/runtime (TinyEngine) to significantly improve the deep learning performance on tiny MCUs.

Computing Map-scale Continuous Mutual Information on Chip in Real Time

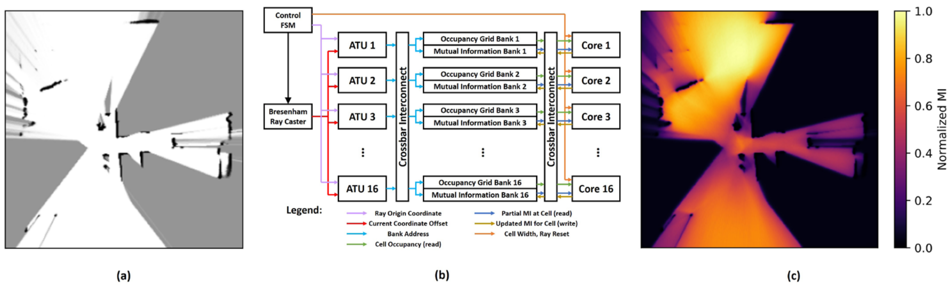
2.07

K. Gupta, P. Z. X. Li, S. Karaman, V. Sze

Sponsorship: NSF RTML 1937501, NSF CPS 1837212

Exploration tasks are essential to many emerging robotics applications, ranging from search and rescue to space exploration. The planning problem for exploration requires determining the best locations for future measurements. A widely-studied metric requires computing the Mutual Information (MI) between the map and future measurements and choosing the location with the highest such MI. Computing the MI for all points in the map is computationally intensive, while computing it at sparse points across the map leads to a suboptimal trajectory.

In this work, we present a scalable, high-throughput hardware accelerator on an FPGA that computes the MI for all cells in a 201x201 grid at 647 Hz while consuming 1.13 W, leading to real time MI computation for the whole map for the first time. This represents a 71x throughput and 36x power consumption improvement over a reference CUDA implementation on a GPU. This improvement results in a shorter exploration trajectory and higher power efficiency.



▲ An example input occupancy grid map (b) Top-level hardware architecture comprised of Address Translation Units (ATU), crossbar interconnects, occupancy grid map memory banks, MI map memory banks, and 16 computation cores. (c) Output MI map.

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Electronic devices, electronics, information processing, integrated circuits.

Sparseloop: An Analytical, Energy-Focused Design Space Exploration Methodology for Sparse Tensor Accelerators

2.08

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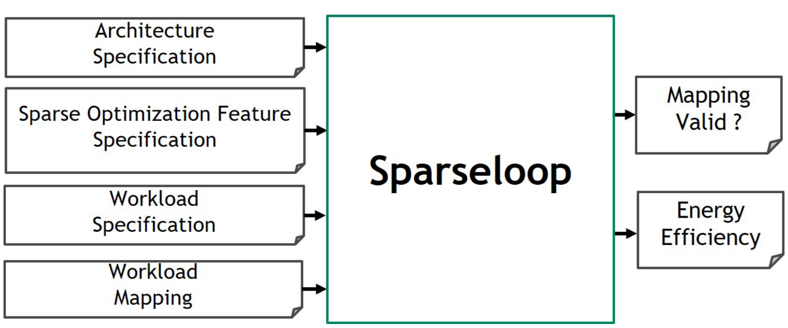
Sponsorship: DARPA (HR0011-18-3-0007)

Recently, a variety of sparse tensor accelerators have been proposed to improve the energy efficiency of sparse tensor computations, which are popular in many applications such as graph algorithms and neural networks. To enable fast design space exploration of such accelerators, parameterizable analytical models, which perform high-level evaluations of a wide range of architectures, are desirable. However, no existing models systematically evaluate the sparse optimization features (e.g., compressed tensor storage) employed by these accelerators. We present Sparseloop, an infrastructure that implements an analytical design space exploration methodology for sparse tensor accelerators. Sparseloop comprehends a wide set of architecture specifications and calculates designs' energy efficiency based on stochastic tensor density models. Sparseloop accurately models sparse tensor accelerators in terms of both energy efficiency improvements (~96% accuracy) and runtime activities (~99% accuracy).



▲ Sparseloop high-level framework. Workload mapping describes the data movement and compute scheduling in space and time of the workload running on the specified architecture.

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Research Interests:
Sensors, systems, robotics.

Balancing Actuation Energy and Computing Energy in Low-Power Motion Planning

2.09

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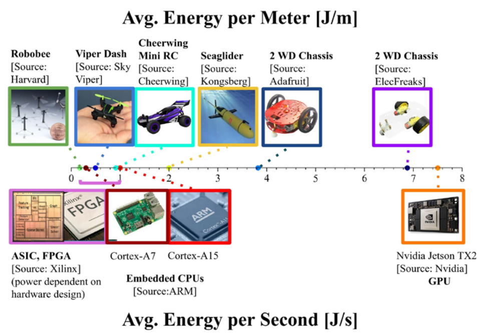
Sponsorship: NSF, Cyber-Physical Systems (CPS) program, through grant no. 1837212

Inspired by emerging low-power robotic vehicles, we identify a new class of motion planning problems in which the energy consumed by the computer while planning a path can be as large as the energy consumed by the actuators during the execution of the path. As a result, minimizing energy requires minimizing both actuation energy and computing energy since computing energy is no longer negligible compared to actuation energy. We propose the first algorithm to address this class of planning problems, called Computing Energy Included Motion Planning (CEIMP).

CEIMP operates like other anytime planning algorithms, except it stops when it estimates that while more computing may save actuation energy by finding a shorter path, the additional computing energy spent to find that path will negate those savings. CEIMP can save on total energy and increase the duration of missions, highlighting the advantage in spending energy to decide when to stop computing for energy-efficient robotics.



◀ The energy consumed by low-power robotic platforms to move 1 meter and the computing energy consumed by embedded computing platforms to compute 1 second approach a similar magni

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Computer vision, machine learning, artificial intelligence.

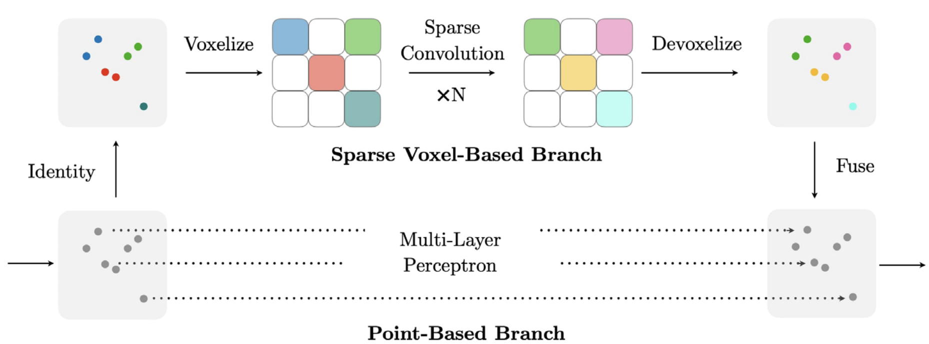
Searching Efficient 3D Architectures with Sparse Point-Voxel Convolution

2.10

H. Tang, Z. Liu, S. Zhao, Y. Lin, J. Lin, H. Wang, S. Han

Sponsorship: MIT Quest for Intelligence, MIT-IBM Watson AI Lab, Xilinx, Samsung

Self-driving cars need to understand 3D scenes efficiently and accurately to drive safely. Given limited hardware resources, existing 3D perception models cannot recognize small instances (e.g., pedestrians) well due to the low-resolution voxelization. To this end, we propose Sparse Point-Voxel Convolution (SPVConv), a lightweight 3D module that equips Sparse Convolution with the high-resolution point-based branch. With negligible overhead, it preserves the fine details from large outdoor scenes. To explore the spectrum of efficient 3D models, we first define a flexible architecture space based on SPVConv and then present 3D Neural Architecture Search (3D-NAS) to search the optimal network architecture. The resulting SPVNAS model is fast and accurate: it outperforms the state-of-the-art MinkowskiNet by 3.3%, ranking 1st on the SemanticKITTI leaderboard. It achieves 3x speedup over MinkowskiNet with higher accuracy, which enables real-time LiDAR perception for autonomous driving.



▲ Sparse Point-Voxel Convolution (SPVConv) equips the sparse voxel-based branch with a lightweight, high-resolution point-based branch which can capture fine details in large scenes.

Single-frame Randomized Probe Imaging Through Deep Residual Learning

2.11

Z. Guo, A. Levitan, M. Deng, G. Barbastathis, R. Comin

Sponsorship: IARPA

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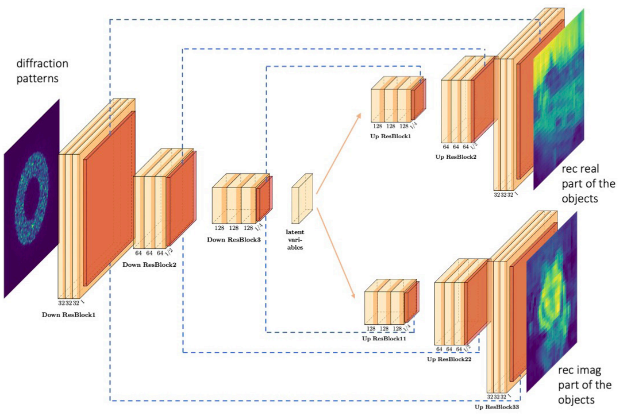
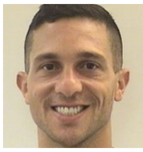
Research Interests:
Information processing.

Randomized Probe Imaging (RPI) is a single-frame diffractive imaging method that uses highly randomized light, rather than a finite support constraint, to generate a unique solution to the phase retrieval problem. However, as with most variations on diffractive imaging, phase retrieval is typically achieved via a computationally intensive and time-consuming iterative reconstruction algorithm. In this work, we propose using a neural network based on deep residual blocks to solve the inverse problem. Once trained, our approach is capable of generating moderate quality reconstructions in a single deterministic step. Furthermore, we propose the use of frequency-attention layers and learning-to-synthesize method to distinct the contributions of different frequencies in the k-space. The dramatic computational speedup using our deep learning approach may enable more important applications to the study of dynamic phenomena in physical science and biological engineering.



◀ Neural network architecture

Session 3: Power



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Research Interests:
GaN.

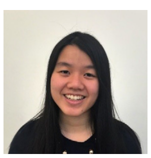
Switching Reliability of GaN Power High Electron Mobility Transistors

3.01

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

GaN electronics constitute a new technology with superior power-handling capabilities compared to those of Si and other semiconductors in many applications. Power management applications typically involve operating the GaN transistors under rapid switch conditions between a high-voltage off-state and a high-current on-state. Depending on the system topology and specification, there are two switching modes applicable to power applications: soft switching and hard switching. The reliability and robustness of GaN transistors under repeated switching is a concern, particularly when operating under hard switching conditions.

In our work we aim to create an experimental framework to evaluate GaN transistor degradation under repeated switching operation and to develop lifetime models to project device survivability under various conditions. To that end we have constructed a unique experimental setup based on the double-pulse testing technique. The system will be able to continuously monitor device parameters pre- and post-stress and quantify device degradation under various switching conditions close to the mode of operation of these transistors in electrical power management applications. The work will provide fundamental understanding of the degradation mechanisms that are at play and will advance the improvement of device design and fabrication process technology.



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Communications, displays, electronic devices, electronics, energy, energy harvesting devices & systems, GaN, integrated circuits, nanotechnology, photovoltaics, power management.

DC-DC Converter Implementations Based on Piezoelectric Transformers

3.02

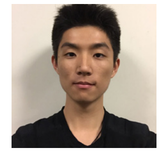
E. Ng, J. D. Boles, J. H. Lang, D. J. Perreault
Sponsorship: Texas Instruments, UROP Direct Funding, NSF Graduate Research Fellowship, Masdar Institute

Power converters play a major role in many applications from high voltage power transmission with electric grids to everyday devices such as phones and computers. As many applications require higher performance and lower power consumption, there has been a trend to make power electronics smaller. Power converters have been difficult to scale down because of their energy storage components. Typical energy storage components, such as transformers are magnetic. The sizes of magnetics-based converters are constrained by the fact that the power densities of magnetics fundamentally decrease at low volumes. Piezoelectrics, scale favorably with reduced size, are a promising energy storage alternative to meet the demands for smaller-volume power electronics. Despite their potential, piezoelectric transformers (PTs) have seen very little use in converters without magnetics. Typically, such converters have limited or unreported efficiencies, but without design considerations for using the PTs most efficiently.

In this work, we systematically enumerate isolated and non-isolated converter operating modes and topologies that best utilize PTs as their only energy storage components. Initial simulations of these converter designs demonstrate promising high-efficiency behaviors including zero voltage switching (ZVS), soft charging of the PT's capacitances, and all-positive instantaneous power transfer across wide operating regions. These results show that PT-based converters can offer high efficiencies with the benefits of the scaling properties of piezoelectrics. This can be helpful in many low voltage applications such as consumer electronics and biomedical devices and particularly that require galvanic isolation.

Multi-Inverter Discrete-Backoff: A High-Efficiency, Very-Wide-Range RF Power Generation Architecture

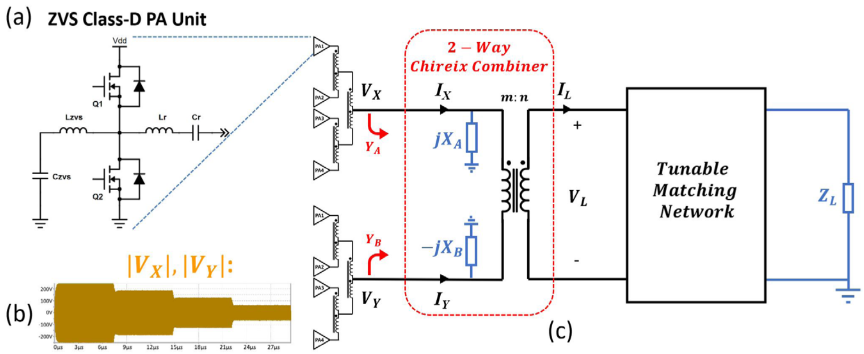
3.03



H. Zhang, A. Al Bastami, A. S. Jurkov, A. Radomski, D. J. Perreault

Sponsorship: MKS Instruments Inc.

Industrial radio frequency (rf) power applications, such as plasma generation for semiconductor etching, require high-frequency rf power over a wide dynamic power range and across variable load impedances. It is desirable in these applications to maintain high efficiency and fast dynamic response. This work introduces a scalable power amplifier (PA) architecture and control approach suitable for such applications. The technique, which we call Multi-Inverter Discrete Backoff (MIDB), losslessly combines the outputs of paralleled switched-mode PAs, and modulates the number of active PAs to provide discrete steps in rf output voltage. It further employs outphasing among sub-groups of PAs for rapid and continuous output power control over a wide range. In doing so, the MIDB-based architecture can maintain high efficiency and fast rf power control across a very wide backoff range.



▲ Example MIDB system implementation: (a) PA unit (b) Achievable voltage magnitudes (|V|) with 4 PA units per PA-group (c) PA system with differential Chireix combiner with outphasing between VX & VY and shunt compensation.

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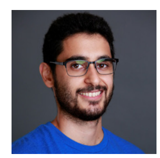
Leveraging Multi-Phase and Fractional-Turn Planar Transformers for Power Supply Miniaturization in Data Centers

3.04



M. K. Ranjram, D. J. Perreault

Sponsorship: Cooperative Agreement between the Masdar Institute of Science and Technology and MIT

Data centers are the backbone of the internet. Their servers represent an important and growing electrical load, and there is strong interest in miniaturizing the supplies that power them. Miniaturization is challenging as it requires both a reduction in volume and an increase in efficiency, and is aggravated in this application by the need for a transformer carrying high current.

This work introduces the concept of a multi-phase and fractional-turn transformer which greatly increases the current handling capability of the transformer. Fractional turns are not possible in conventional transformer constructions, but are enabled here by careful consideration of the connections between active switching devices and the passive copper and magnetic material comprising the transformer. A split-phase fractional turn transformer is estimated to reduce loss by 3.1x compared to a conventional transformer construction in the same volume, demonstrating its clear miniaturization benefit.

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Exploring Power Conversion Based on Switched Capacitors and Piezoelectric Resonators

3.05

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Batteries, biological devices & systems, bioMEMS, electronic devices, electronics, energy, energy harvesting devices & systems, integrated circuits, nanomaterials, power management.

Power electronics are essential to the advancement of industries such as grid energy storage, transportation, and biotechnology. The demand for smaller, lighter, and more economical power converters will require energy conversion technologies with significantly higher power density and efficiency. The miniaturization of converters is limited by magnetic storage elements: the power density of magnetics fundamentally decreases with volume at fixed frequencies. Switched capacitor (SC) converters, which use capacitors instead of magnetics, have offered improved efficiency and power density over high step-down ratios. Since the voltage regulation capabilities for purely-SC converters at high efficiency is very narrow, they are often used in conjunction with magnetic components. One alternative to magnetics is the piezoelectric resonator (PR), which provides high power density capabilities at lower volumes and allows for high efficiency in dc-dc converter designs across wide voltage conversion ranges. However, PR-based architectures explored to date have limited voltage step-down capabilities. By combining the switched capacitor and piezoelectric resonator technologies, their advantages can be leveraged to address their individual drawbacks.

In this work, we explore possible dc-dc converter implementations based on cascaded SC and PR stages. We focus on implementing soft-charging, a constraint that implies that the voltages of the PR and SCs change through resonance, so that the energy stored in their capacitances can be reallocated rather than consumed. Our initial simulations demonstrate that this is a feasible mechanism for achieving high step-down ratio with improved regulation capabilities without the use of magnetic components. Consequently, these PR-based switched capacitor converters are promising for miniaturized power conversion, especially for applications such as logic-level power supplies, biomedical devices, and consumer electronics.

Closed Loop Control for a Piezoelectric-Resonator Based DC-DC Power Converter

3.06

J. Piel, J. Boles, D. Perreault

Sponsorship: Texas Instruments, NSF GRFP, UROP

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Electronics today can vary greatly in power requirements, and power electronics are necessary to power these devices from standard sources. They are necessary for many devices like computers, mobile phones, household appliances, or even electric vehicles. Reducing the size of power converters allows them to be more cost effective and used in an even wider range of applications. Traditional DC-DC power converters make use of magnetics for energy storage, but these are less efficient and power dense when scaled down to small sizes. Our prior research has explored the use of piezoelectric resonators (PRs) as an alternative energy storage for DC-DC converters, and we successfully designed a magnetics-less PR based converter. However, our initial prototypes depended on manual and open loop switching time configuration, meaning the converter cannot dynamically handle transients or adjust operation when the load or temperature changes.

This work presents a new closed loop control scheme for the PR based DC-DC converter. The main challenges of implementing this control scheme involve cycling the PR between three different voltages while making sure the switch and PR capacitances do not instantaneously change during switching. The controller achieves this by sensing PR terminal voltages and detecting current zero-crossings, then implements a P-I feedback loop to adjust frequency and produce the desired power output. Initial simulations of the control have shown promising results with a relatively simple implementation. Implementation of this closed-loop control scheme will allow the PR based converter to operate on its own, paving the way for use of these small and efficient DC-DC converters in commercial applications.

MEMS Compatible Micro Rocket Engine using Steam Injector and Electric Fuel Pump

3.07

J. Protz

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

Micro-fabricated miniature chemical rocket engines have been an active area of research at MIT and elsewhere for two decades; they are a compelling propulsion option for small launch vehicles and spacecraft. As originally proposed by the PI, miniaturized steam injectors like those used in Victorian-era steam locomotives are viable as a pumping mechanism at these scales and offer an alternative to pressure-feed or high-speed turbo-pumps. Past work by the PI explored partially-pressure-fed and hybrid engine designs. The latest phase of work has focused on designing and implementing a whole-engine mock-up or test article that simultaneously integrates a steam injector, boiler, decomposition chamber, fuel injector, thrust chamber, and electric fuel pump while retaining compatibility with 2D MEMS fabrication. This newest approach uses a battery and electric pump to replace the pressure-feed of past designs, greatly simplifying implementation and the sourcing of components.

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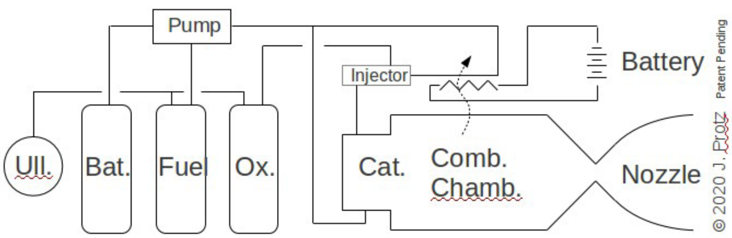

▲ Schematic representation of engine and (b) engineering mock-up in brass of an engine.

Session 4: Optics and Photonics

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Lasers, optoelectronics, photonics, quantum devices.

Terahertz Light Sources by Electronic-Oscillator-Driven Second Harmonic Generation in Extreme-Confinement Cavities

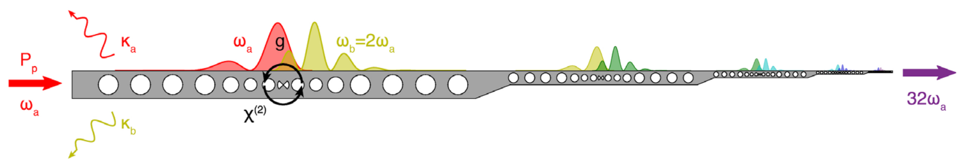
4.01

L. Ateshian, H. Choi, M. Heuck, D. Englund

Sponsorship: DARPA, DRINQS, NSF GRFP

With their enormous technological importance in communications, medicine, industry, and other fields, lasers driven by population inversion comprise the majority of sources of coherent optical radiation. Yet, it remains a challenge to produce high-power oscillators in the spectral range of 0.1-10 THz (the “terahertz gap”), a desirable frequency band for applications such as spectroscopy, security, and high-speed wireless communications.

Here, we propose a way to produce coherent radiation spanning the THz gap by efficient second-harmonic generation (SHG) in low-loss dielectric structures, starting from electronic oscillators (EOs) in the ~100 GHz range. We introduce hybrid THz-band dielectric cavity designs that combine (1) extreme field concentration in high-quality-factor resonators with (2) nonlinear materials enhanced by phonon resonances. This approach would enable efficient, cascaded parametric frequency converters, representing a new generation of light sources extensible into the mid-IR spectrum and beyond.



▲ Schematic of spectrum-spanning nonlinear frequency synthesis approach in photonic crystal cavities.

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GaN, III-Vs, integrated circuits, lasers, light-emitting diodes, optoelectronics, photonics, photovoltaics, sensors, SiSiGe and Ge.

High-performance On-chip Digital Fourier Transform Spectrometers

4.03

G. Micale, C. Rios, J. Hu

Optical spectrometers are extensively used for sensing, optical network monitoring, and materials analysis. Conventional spectrometers are bulky and expensive instruments, which confines them to laboratory settings. On-chip digital Fourier Transform spectrometers (dFTS) leverage the miniaturization of integrated photonics and the multiplex advantage of Fourier Transform spectroscopy to offer significant size, weight, power, and cost advantages to bench-top instruments. However, past versions of this architecture have been limited in spectral resolution and operation speed. To overcome these limitations, we explore two new dFTS designs to expand the performance capabilities and the potential applications. Our first design implements a dFTS with up to 1024 reconfigurable optical paths, or channels, which enables 20-40 pm high-resolution spectral imaging. Our second device substitutes electro-optical phase modulators for the speed-limiting thermo-optical phase shifters used in previous designs. The phase modulators are based on forward-biased PIN diodes and yield a π phase shift with a voltage $V\pi = 1.23V$. We created an O-band 64-channel design to account for the extra losses associated with electro-optic modulation. These two architectures harness standard CMOS-compatible photonic components for mass fabrication. Their performance holds promise for many applications like optical spectrum analysis, medical imaging, chemical sensing, and RF spectroscopy.

Imaging Transparent Objects Through Dynamic Scattering Media Using Recurrent Neural Networks

4.04

Iksung Kang, Subeen Pang, Qihang Zhang, Nicholas Fang, and George Barbastathis

Sponsorship: IARPA (FA8650-17-C9113), Korea Foundation for Advanced Studies

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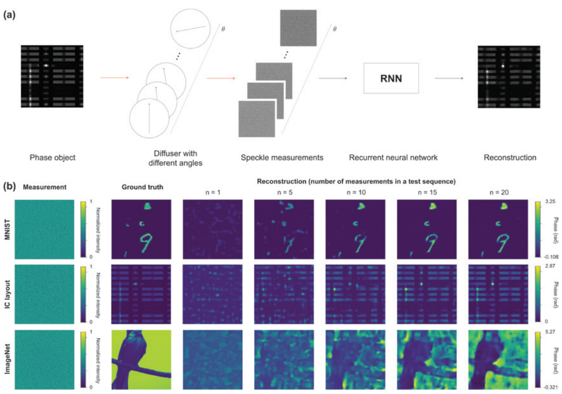
Research Interests:
Information processing, lasers, applied optics, machine learning, computational imaging.

Transparent objects in biological imaging and X-ray imaging are imaged by solving inverse problems based on their diffraction intensity patterns. However, scattering process induced by their complex interiors complicate inverse problems with a severity depending on the statistics of the refractive index gradient and contrast profiles. Recently, static neural networks were used to retrieve original information out of scattering. Here, we propose a novel dynamical machine learning approach to image phase objects through arbitrary diffusers. This architecture is adopted to strengthen and exploit the correlation among scattering patterns during the training and testing process. To impart dynamics, we use the on-axis rotation of a diffuser and utilize multiple speckle measurements from different angles to form a sequence of images for training. Our recurrent neural network (RNN) architecture effectively discard any redundancies and enhance/filter out the static pattern, that is the quantitative phase information of transparent objects. This method is also applicable to other imaging applications the involve any other spatiotemporal dynamics.



◀ (a) Speckle measurements of an object are recorded by a camera after different angles of diffuser, which are processed with a recurrent neural network. (b) Progressions of reconstructions according to the number of measurements in a test sequence.

Integrated-Photonics-Based Holographic Display for Augmented Reality

4.05

M. Notaros, J. Notaros, T. Dyer, M. Raval, C. Baiocco, M. R. Watts

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

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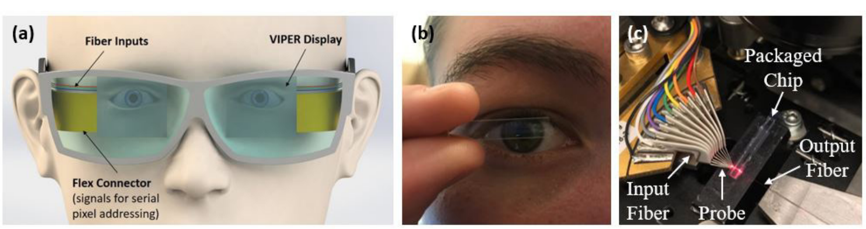
Displays, photonics.

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

In this talk, recent advances in the development of a novel integrated-photonics-based holographic display, will be reviewed. The display consists of a single transparent chip that sits directly in front of the user's eye and projects 3D holograms that only the user can see using amplitude- and phase-encoded liquid-crystal-based integrated optical phased arrays. It presents a highly discreet and fully holographic solution for the next generation of augmented-reality displays.



▲ (a) Diagram of the chip-based direct-view near-eye VIPER head-mounted display. (b) Photograph of a transparent VIPER chip held in front of an eye. (c) Photograph of a VIPER photonic chip packaged with liquid crystal on an experimental setup.

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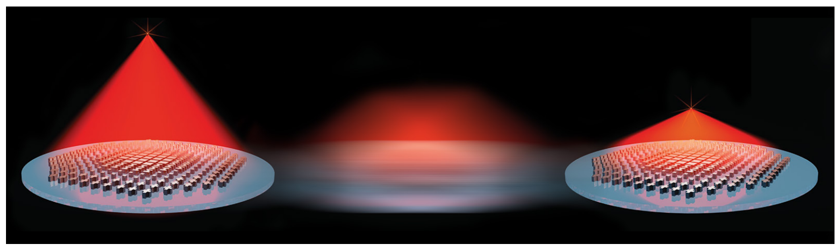
High-performance Non-mechanically-tunable Meta-lens

4.06

M. Y. Shalaginov, S. An, Y. Zhang, F. Yang, P. Su, V. Liberman, J. B. Chou, C. M. Roberts, M. Kang, C. Rios, Q. Du, C. Fowler, A. Agarwal, K. Richardson, C. Rivero-Baleine, H. Zhang, J. Hu, T. Gu

Sponsorship: DARPA Extreme Optics and Imaging (EXTREME) Program (HR00111720029)

Optical metasurfaces, i.e., ultra-thin arrays of sub-wavelength antennae, have enabled a new range of photonic devices with unprecedented functionalities in sculpting wavefronts and substantially reduced form-factor. Recently special interest has been drawn to a class of so-called 'active metasurfaces', whose optical properties can be modulated post-fabrication by non-mechanical effects. A variety of tuning mechanisms have been harnessed; however, demonstrated meta-optical devices often incur narrow tuning ranges and low optical efficiencies. Here, we implemented an active varifocal meta-lens based on phase-change materials which offers 1) aberration-free performance across arbitrary optical states; 2) extremely low crosstalk of nearly 30 dB; and 3) considerably enhanced focusing efficiency exceeding 20% in both states with a clear pathway for further improvement. This advancement will further unveil a new cohort of exciting applications of active metasurfaces in imaging, sensing, display, and optical ranging.



▲ Illustration of a non-mechanically-actuated varifocal meta-lens made of phase-change material (Ge2Sb2Se4Te1). Focal plane position is switched between the two states depending on the optical material state (amorphous or crystalline).

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The Effect of O:N Ratio of a HfOxNy Interlayer on Triplet Energy Transfer in Singlet-fission-sensitized Silicon

4.07

N. Wong, C. F. Perkinson, W. A. Tisdale, M. A. Baldo

Sponsorship: U.S. Department of Energy

With the climate changing, the Sun is a major contender as a renewable energy resource. However, silicon photovoltaics, the current industry standard, are approaching their theoretical efficiency limits. One way to boost efficiencies beyond this limit is to sensitize the silicon by using a material that can perform singlet exciton fission (SF), a carrier multiplication process that can create two electrons from a single photon. Successful transfer of these two electrons to silicon can result in increased photocurrent and improved efficiencies. Recently, our group demonstrated the first proof-of-concept device incorporating tetracene as the SF material to produce additional carriers that are transported via a thin layer of hafnium oxynitride (HfOxNy) to silicon.

With the aim of improving these devices, our research focuses on understanding what properties are necessary for the transport layer between tetracene and silicon, and the mechanism for the transfer process. In this work, the defect density of the HfOxNy transport layer is varied by changing the oxygen to nitrogen ratio and different interlayer thicknesses are studied to look at the role of defect states on the transfer process from tetracene to silicon. The transfer efficiency is inferred via magnetic field modulation of the photoluminescence from silicon. The results form a preliminary basis for unravelling the exact mechanism of transfer, which will be studied in the future using time-resolved second harmonic generation (SHG) spectroscopy. Ultimately, knowledge of the specific transport layer material properties and mechanistic insights will form the groundwork for improved material choices and commercializing the use of SF to boost silicon photovoltaic efficiencies.

Multiplexed Raman Sensors using Swept-Source Excitation

4.08

N. Persits, J. Kim, Z. Li, R. Ram

Sponsorship: FDA3

Spontaneous Raman spectroscopy is routinely used in pharmaceutical production, chemical analysis, and the semiconductor industry for characterization of structural features, strain, and doping. Standard Raman systems require dispersive spectrometers and often specialized cooled CCD detectors to compensate for the low signals, making them prohibitively expensive and bulky. In this work we introduce and demonstrate a novel Raman system architecture using a swept-source laser excitation, replacing the spectrometer. The laser is delivered through optical fibers to custom-made Raman probes, which are designed to be compatible with either single mode or telecom-standard multimode optical fibers. Each probe delivers the excitation light onto a sample and collects the Raman signal which is then detected using a narrow optical filter in front of a room-temperature high gain Si photodiode. With a standard telecom optical switch, we can multiplex up to 16 channels and deploy remote probes using an optical fiber network. As an initial proof-of-concept we present the spectra collected with our probes for both solid polystyrene and liquid urea solutions and further show that the acquired spectra has comparable SNR to that collected with our lab-built bench top Raman system. We believe this new system in which a single tunable laser can serve a distributed sensor network, can significantly reduce the space and cost of current spectrometer-based Raman systems and promote the use of Raman for online process control.

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Biological devices & systems, bioMEMS, lasers, light-emitting diodes, medical devices & systems, optoelectronics, photonics, sensors.

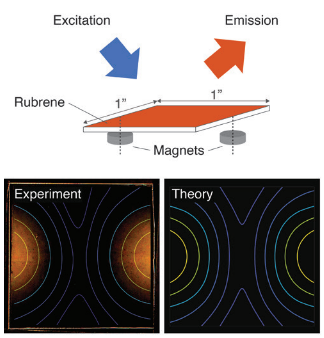
Magnet Field-switchable Laser via Optical Pumping of Rubrene

4.09

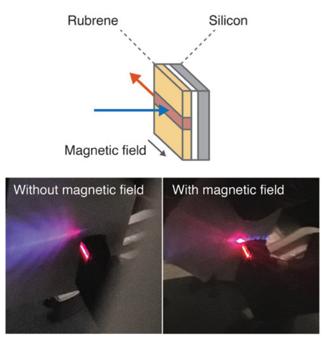
C. F. Perkinson, M. Einzinger, J. Finley, M. G. Bawendi, M. A. Baldo

Sponsorship: U.S. Department of Energy (DE-FG02-07ER46454), NSF Graduate Research Fellowship (1122374)

Optical imaging of magnetic fields is used in spintronics, magnetic resonance imaging, and radiology. Most conventional approaches to magnetic field imaging rely on expensive crystalline materials or garnets, but the cost of these materials make them poorly suited to high-area imaging. Magnetic sensing applications may benefit from cheaper magnetically-active dyes. We demonstrate that the well-studied organic molecule rubrene can be used to spatially resolve magnetic fields. Furthermore, we report a 460% enhancement in rubrene brightness under a 0.4 T magnetic field in a first-of-its-kind magnetic field-switchable laser. We attribute the high magnetic sensitivity of rubrene to the magnetic field dependence of singlet fission, a process whereby one spin-singlet excitation splits into two spin-triplet excitations. These results suggest that rubrene—and other organic molecules that exhibit singlet fission—are promising candidates for low-cost, high-sensitivity magnetic imaging.



Spatially-resolved magnetic field sensing



Switchable laser for magnetic field sensing

◀ (Left) Spatially-resolved magnetic field sensing through modulation of rubrene emission intensity. (Right) Optically-pumped waveguide laser, showing magnetic field switching between non-lasing and lasing modes.

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Research Interests:
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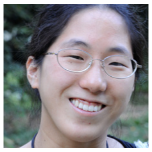

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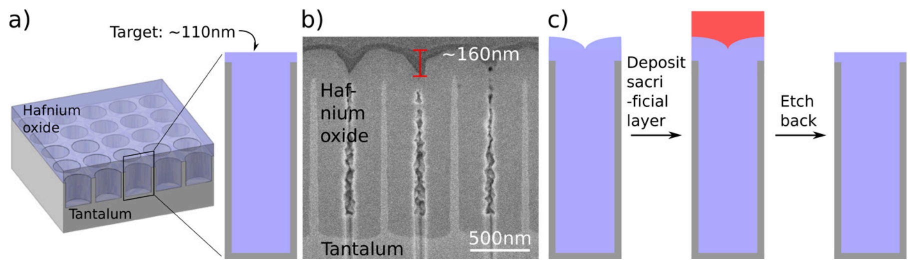
Hafnia-Filled Photonic Crystal Emitters for Mesoscale Thermophotovoltaic Generators

4.10

R. Sakakibara, V. Stelmakh, W.R. Chan, R. Geil, M. Ghebrebrhan, J.D. Joannopoulos, M. Soljačić, I. Čelanović

Sponsorship: Army Research Office, U.S. Department of Energy

Thermophotovoltaic (TPV) systems are promising as small scale, portable generators for power sensors, small robotic platforms, and portable computational and communication equipment. In TPV systems, an emitter at high temperature emits radiation that is then converted to electricity by a low bandgap photovoltaic cell. One way to increase both TPV power and efficiency is to use two-dimensional, hafnia-filled-and-capped tantalum photonic crystals (PhCs); they enable spectral tailoring of thermal radiation for a wide range of angles. However, two key features are hard to realize simultaneously: a uniformly filled cavity and a thin capping film. Cavity-filling leads to a capping film that is both thick and uneven, so that trying to thin the film removes hafnia from within the cavity. Here, we present a method to reduce the film roughness and better control the thickness. Improved PhCs can pave the way toward high-performance TPV micro-generators for off-the-grid applications.



▲ a) The ideal filled photonic crystal (PhC) should have a flat and thin capping layer. b) The fabricated PhC cross section shows a thick and uneven capping film. c) A planarization and etch back process is used to reduce both roughness and thickness.

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2D materials, bioMEMS, nanotechnology, optoelectronics, sensors.

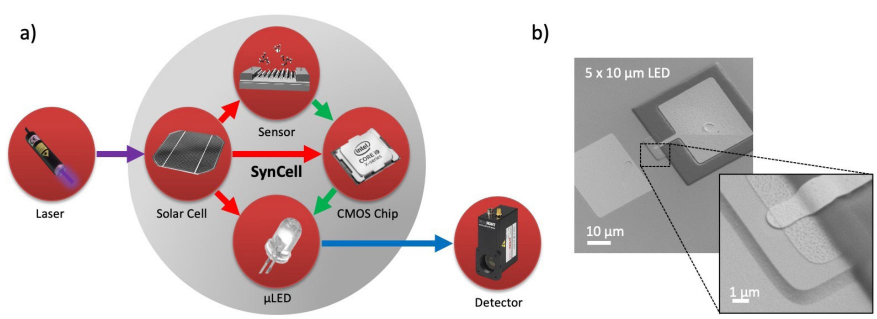
GaN μLEDs for Microsystem Optical Communications

4.11

S. Spector, M. Hempel, T. Palacios

Sponsorship: Air Force Office of Scientific Research, MIT Experiential Learning Opportunity

Electronic systems smaller than 50 μm are promising for ubiquitous sensing; however, wireless communication with such systems is challenging since RF communication is inefficient at the micron scale. This motivates the use of optical communications for micro-devices, which must be low-power due to the size constraint on solar cell surface area. Here we present an analysis of blue GaN microLEDs (μLEDs) for optical communications with 50 x 50 μm2 sensor microsystems called SynCells. We analyzed μLEDs with sizes from 5 x 10 μm2 up to 150 x 150 μm2, developing a test setup that can detect an LED driven by only 1 nW. We found higher external quantum efficiency (EQE) for larger μLEDs; also, EQE increased with current density up to a peak value, after which we observed an efficiency droop resulting from Auger recombination. GaN μLEDs operating at maximally efficient current density will be able to produce detectable optical signals at sufficiently low power for practical use in SynCells.



▲ a) Block diagram of SynCell operation including μLED and photomultiplier tube detector for optical communication; b) SEM image of a 5 x 10 μm^2 GaN μLED.

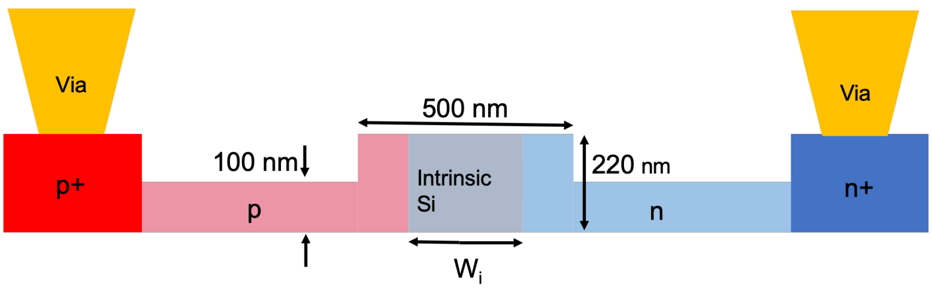
Cryogenic Operation of Silicon Photonic Modulators Based on DC Kerr Effect

4.12

U. Chakraborty, J. Carolan, G. Clark, D. Bunandar, G. Gilbert, J. Notaros, M. Watts, D. Englund

Sponsorship: NDSEG Fellowship, EU H2020 MSCA, AFOSR, DARPA, MITRE Corporation

Reliable operation of photonic integrated circuits (PICs) at cryogenic temperatures can enable new capabilities for emerging technologies such as quantum and low-power cryogenic computing. The silicon-on-insulator platform is highly promising for large-scale PICs due to its exceptional manufacturability, CMOS-compatibility and high component density. Fast, efficient and low-loss modulation at cryogenic temperatures in silicon, however, remains an outstanding challenge, as the performance of standard thermo-optic and plasma dispersion modulators can be significantly degraded at low temperatures. In this work, we demonstrate DC-Kerr-effect-based modulation at a temperature of 5 K at GHz speeds in a silicon photonic device fabricated exclusively within a CMOS-compatible process without the addition of exotic nonlinear optical materials. This work opens up the path for the integration of DC Kerr modulators in large-scale PICs for cryogenic classical and quantum computing applications.



▲ Schematic of integrated silicon photonic PIN modulator

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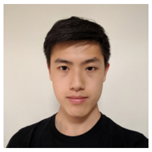
Session 5: Quantum Technologies



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Research Interests:
Information processing, nanotechnology, photonics, quantum devices.

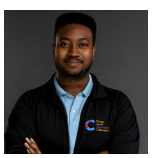
A Polarization Encoded Photon-to-Spin Interface

5.01

K. C. Chen, E. Bersin, D. Englund

Sponsorship: National Science Foundation, U.S. Army Research Laboratory

The central goal of quantum communication is to deliver quantum information in a way that is resilient against eavesdropping. One notable approach is the measurement-device-independent quantum key distribution (MDI-QKD) protocol [1,2], in which a secret key is shared between two parties connected by quantum and classical channels. Essential to this architecture, however, is the ability to faithfully transfer quantum states between two distant qubits. Here, we propose an integrated photonics device for mapping qubits encoded in the polarization of a photon onto the spin state of a cavity-coupled artificial atom: a "Polarization-Encoded Photon-to-Spin Interface" (PEPSI). We perform theoretical analysis of the state fidelity's dependence on the device's polarization extinction ratio and atom-cavity cooperativity. Furthermore, we explore the rate-fidelity trade-off through analytical and numerical models. In simulation, we show that our design enables efficient, high-fidelity photon-to-spin mapping.



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Research Interests:
Nanomanufacturing, nanomaterials, quantum devices, quantum information science.

Nonlinear Pulse Compression for Single Flux Quantum (SFQ) Compatible Qubit Readout

5.02

G. Cunningham, E. J. Porter, K. P. O'Brien

Sponsorship: Harvard Graduate School of Arts and Sciences Prize Fellowship

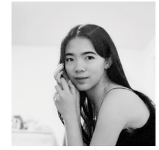
Superconducting (SC) qubits are a promising candidate for realizing fault tolerant quantum computing due their fast gate operation and simple integration with existing conventional electronics. On a small-scale, SC qubits have allowed high-fidelity coherent control of quantum simulations, high sensitivity of magnetic phenomena, and the study of atomic and optical processes beyond conventional limits. However, the large number of required cables between the room temperature and cryogenic electronics limits the feasibility of thousand to million qubit quantum computers. Classical cryogenic logic based on single flux quantum (SFQ) technology may provide an advantage over room temperature electronics for qubit readout and control, but scalable schemes for interfacing SFQ logic with quantum processors are in their infancy. In this work, we propose a frequency-multiplexed interface between the quantum processor and SFQ logic at the cryogenic stage, based on nonlinear pulse compression and soliton dynamics in a Josephson transmission line (JTL). Pulse amplification of single photon level processor output to voltage amplitudes consistent with SFQ pulses of ~ps duration is addressed via Josephson traveling wave parametric amplification (JTWPA). Nonlinear pulse compression is addressed via engineering the dispersion of the JTL through varying the Josephson junction (JJ) current bias in junctions along the propagation direction.

A High-Dense Arrays of Diamond Vertical Cavity Towards a Scalable Quantum Network

5.03

Y. Duan, K. C. Chen, D. R. Englund, M. E. Trusheim

Sponsorship: U.S. Army Research Laboratory Center, The Center for Integrated Quantum Materials (CIQM)



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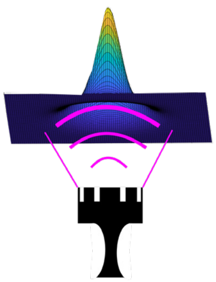
Research Interests:
2D materials, actuators, electronics, energy, energy harvesting devices & systems, MEMS & NEMS, sensors, systems.

A scalable quantum network will require a large number of long-lived qubits that are efficiently coupled to optical modes. Quantum emitters in diamond such as the nitrogen vacancy (NV) center and the group IV emitters exhibit excellent optical and spin coherence properties suitable for quantum network applications[1-3]. However, they spontaneously emit into many spatial and spectral modes, resulting in low spin-photon entanglement generation rates. Spin-photon entanglement efficiency is parametrized by the figure of merit eta = eta_1 eta_2, where eta_1 quantifies the emission into the cavity-coupled zero phonon line, and eta_2 is the farfield collection efficiency. Waveguide-coupled one- and two-dimensional photonic crystal cavities currently set the state-of-the-art spin-photon interface, which achieves atom-cavity cooperativity >> 1[4] and efficient emission into a single electromagnetic mode. The use of in-plane photonic waveguides, however, limits the achievable density of efficiently-coupled cavities since each waveguide must be individually coupled off-chip. Here we propose a vertically loaded diamond microdisk resonator (VLDMoRt) with perturbative gratings. In finite-difference time-domain(FDTD) simulations, our device achieves both high emitter-cavity and efficient free-space coupling through emission into the out-of-plane free-space modes. The high density of efficient cavity(10^4/mm^2) coupling to spatially multiplexed free space modes makes it a promising candidate for a quantum network platform.



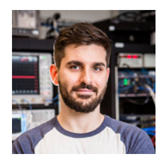
◀ A schematic side view of the cavity with partially etched gratings coupled to free space within a certain collection angle.

Simulating Quantum Transport and Localization Using a Superconducting Quantum Processor

5.04

A. Karamlou, J. Braumüller, B. Kannan, D. Kim, M. Kjaergaard, A. Melville, B. M. Niedzielski, Y. Sung, A. Vepsäläinen, R. Winik, Y. Yanay, J. L. Yoder, C. Tahan, T. P. Orlando, S. Gustavsson, W. D. Oliver

Sponsorship: NSF GRFP (2018265551). NSF (PHY-1720311, 1839197); DOD via MIT Lincoln Laboratory under U.S. Air Force Contract No. FA8721-05-C-0002.



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Quantum devices, quantum simulation, quantum computation.

Quantum materials will have a major impact on the future of nanotechnology. However, limitations in our understanding of the behavior of these materials due to the complex many-body interactions governed by the laws of quantum mechanics serves as a barrier to accessing their full potential. Quantum transport plays an important role for electron and phonon conduction in interacting condensed matter systems in the presence of inelastic scattering. Using an array of superconducting qubits, we emulate a 1-dimensional and 2-dimensional tight-binding lattice in various parameter regimes. We first observe ballistic transport in quantum random walks on a lattice with uniform site energies. Next, we study the absence of diffusion in a disordered lattice due to Anderson localization and experimentally extract the scaling of the inverse participation ratio as a proxy for the degree of localization. Finally, we simulate the tight-binding model in the presence of a dc-field, leading to Wannier-Stark localization and Bloch oscillations. Our methods in performing these experiments, verified by the close match between the experimental results and theory, serve as a blueprint for simulating the behavior of even more complex quantum materials which would be intractable using a classical computer.

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Research Interests:
2D materials, quantum devices, spintronics.

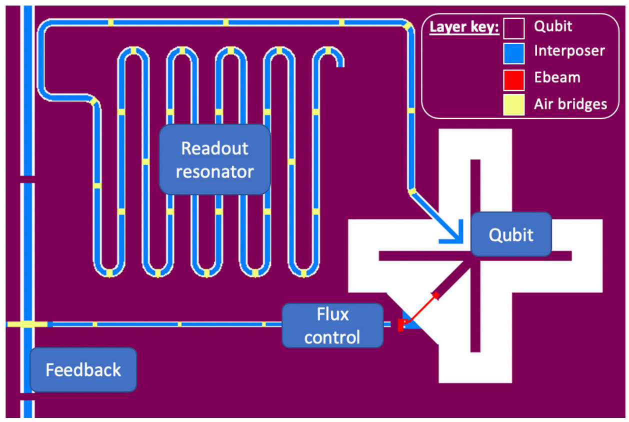
Design of Superconducting Qubit Lattices using Flip Chip Technology

5.05

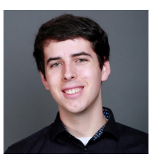
S. Muschinske, P.M. Harrington, J. Braumueller, M.E. Schwartz, T. Hazard, D. Rosenburg, J. Yoder, W.D. Oliver

Sponsorship: DOE, LPS, NASA

Quantum computers enable the analog simulation of currently inaccessible quantum lattices due to their substantial computational speedup compared to their classical counterparts. In this context, superconducting qubits offer advantages over other qubit modalities, such as trapped ions and neutral atoms, due to the relative ease of individual qubit control and readout, as well as a broad tunability of qubit frequencies and couplings. However, extensible superconducting qubit processors must support the interconnect routing required for large 2D qubit arrays. Here, we incorporate flip-chip 3D integration technology in the design of mesoscale qubit lattices. This allows us to reduce interconnect density and crosstalk and enables the control and readout of all qubits in large processors. As a first demonstration, we have designed a 4x4 grid of qubits for use in the analog simulation of the Bose-Hubbard model, relevant for a wide variety of condensed matter physics.



◀ Example of a 3D integrated grounded transmon qubit that is read out using a dispersively-coupled lambda/4 resonator and uses a lambda/2 Purcell filter to reduce qubit loss. The two layers of the flip chip technology are denoted as the qubit and the interposer layer.



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Research Interests:
Nanotechnology, photonics, quantum devices.

Nonlinear Analysis and Simulation of Pulse Compression Circuits for Qubit Readout

5.06

E. J. Porter, G. Cunningham, K. P. O'Brien

Sponsorship: MIT Undergraduate Research Opportunities Program

Superconducting circuits are one of the most promising modalities of quantum computing. They can also be used to make highly energy efficient digital signal processing chips. Single flux quantum (SFQ) circuits make use of Josephson transmission lines (JTLs) to process picosecond scale flux solitons with voltages on the order of millivolts. These pulses propagate through the transmission line without loss. The nonlinear properties of JTLs allow for behaviour such as temporal self-focusing, a feature of the non-zero third order nonlinear susceptibility. This phenomena is relevant for processing photon population based readout pulses from qubits with SFQ control circuitry. Pulses from traditional readout resonators have widths on the order of 100 ns and voltages on the order of 100s of nanovolts, thus can not be sustained in a JTL. In this work, we will characterize a Josephson transmission line which will allow for the interfacing between qubits and SFQ circuits via nonlinear pulse compression. The dynamics of pulse shaping will be explored through transfer matrices and nonlinear analysis. Parameter exploration and verification will be done through WRspice, a SPICE based circuit simulator with a built in Josephson junction model. Previous work in this area has involved coupling an SFQ timing delay circuit to a Josephson Photomultiplier, but has not explored the possibility of directly reading out processed pulses from the resonator. Interfacing between superconducting qubits and SFQ circuits will allow for novel qubit readout schemes improving scalability and moving towards the goal of a fault-tolerant quantum computer.

Superconductor-Spin Transduction for Hybrid Quantum Computing and Networking

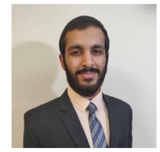
5.07

H. Raniwala, M. Trusheim, M. Eichenfield, L. Hackett, W. Oliver, D. Englund

Sponsorship: MITRE, NSF, Army Research Laboratory

Superconducting circuit (SC)-based quantum devices enable high-speed, high-fidelity manipulation of artificial atom quantum bits (qubits). These devices herald a new generation of computing capabilities that promise far-reaching applications in drug simulation for pharmacological development, quantum-key distribution (QKD) for secure communications, and new methods of processing big data. However, inherent obstacles of noise and scalability issues impede SC quantum devices from achieving fault-tolerant computing and networking capabilities.

In this work, we experimentally demonstrate the first steps toward a quantum state transducer that converts microwave photons from SC devices to electron spin states in solid-state color centers via a phononic signal bus. This multi-stage converter seeks to circumvent the issues SC qubits face by transferring their information to a long-lived, network-compatible quantum modality as a first step towards hybrid quantum computing systems.



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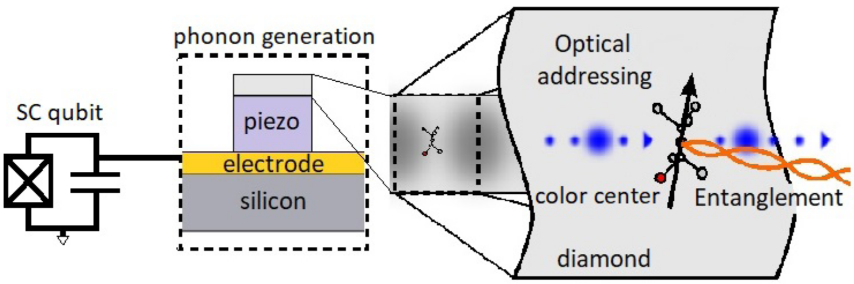
Research Interests: Lasers, photonics, quantum devices, transducers.



▲ Transducer cross section with SC qubit connection and diamond optical addressing highlighted.

Tracking the Evolution of Nitrogen Vacancy Optical Properties Throughout Fabrication

5.08

M. Sutula, M. Walsh, E. Bersin, I. Christen, K. Chen, M. Trusheim, D. Englund

Sponsorship: NASA, CIQM, NSF EFRI-1641064, MIT Lincoln Laboratory, MIT EECS

Color centers in diamond have emerged as a leading platform for quantum information. In particular, the nitrogen vacancy (NV) defect center in diamond has excellent spin properties and a coherent optical interface, making it a compelling candidate for use in many computing and networking architectures. The readout efficiency of the spin-photon interfaces can be improved by fabricating structures such as nanopillars or cavities around the NVs. However, the impact that nanofabrication has on optical properties has not been thoroughly studied. Here, we measure NV emission frequencies and linewidths via photoluminescence excitation in a home-built confocal microscope, and track them throughout processing. We propose and implement an approach which relies on relational position tracking of hundreds of NVs to revisit emitter sites after each processing step, allowing direct comparison of the optical properties of each emitter throughout fabrication. The results have implications not only for quantifying the stability and robustness of NV optical properties, but also for the development of automated processes to systematically characterize and re-locate color center sites. Understanding the evolution of NV optical properties will enable high-yield integration of high-quality color centers into near-term quantum information applications.

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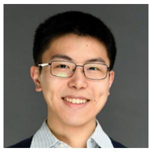

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Research Interests:
Electronic devices, information processing, integrated circuits, photonics, quantum devices.

5.09

Engineering Purely Nonlinear Coupling with the Quarton

Y. Ye, K. Peng, M. Naghiloo, G. Cunningham, K. P. O'Brien

Sponsorship: MIT Center for Quantum Engineering via support from the Laboratory for Physical Sciences (H98230-19-C- 0292)

Nonlinear coupling is essential to quantum operations but it is generally perturbative (weak) to linear coupling. In superconducting circuits, linear coupling hybridize localized modes which leads to undesirable effects like self-Kerr in photon modes and weak, non-ideal nonlinear coupling. Here, we propose using a quarton to facilitate purely nonlinear coupling between two linearly decoupled transmon qubits. The quarton's zero $\phi 2$ potential leads to nonlinear coupling strengths that exceed previous couplers by an order of magnitude; and the quarton's positive $\phi 4$ potential can cancel the negative self-Kerr of modes, causing atomic modes to behave more photonic. We show a >1 GHz nonlinear coupling, in the localized / bare mode basis, between two linearized modes with zero self-Kerr; the resulting giant cross-Kerr between photons is promising for applications such as microwave photon detection and bosonic qubit control.

Session 6: Biotechnologies

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Research Interests:
Actuators, batteries, biological devices and systems, bioMEMS, electronic devices, electronics, energy, energy harvesting devices and systems, fieldemitter devices, lasers, MEMS and NEMS, nanomanufacturing, nanomaterials, nanotechnology.

Optimization and Design of Umbo Microphone for Fully Implantable Assistive Hearing Devices

6.01

B. G. Cary, J. Z. Zhang, E. S. Olson, H. H. Nakajima, J. H. Lang
Sponsorship: NIH

Assistive hearing devices have enabled the restoration of one the most important senses. These technologies have changed the lives of millions, but there are also hindrances which arise. Today's hearing devices are bulky, can only be worn during the day, and do not function well in noisy environments. These issues can be addressed by implantable devices. As these devices are entirely encapsulated in the body, these implants can take advantage of the natural acoustic filtering of the ear, are not a detriment to a person's ability to be physically active and can be worn at night. However, microphones within these devices are a limiting factor.

We present a drum-like microphone which captures the nanometer-scale motion of middle-ear bone structures driven by the eardrum. As we have successfully demonstrated a proof-of-concept, our next goals are to optimize the design and fabrication methods. Transduction of acoustically driven vibration into an electrical signal is achieved utilizing PVDF, a piezoelectric film. This has been characterized through equations which couple solid mechanics to electromagnetics. In order to achieve a high signal-to-noise ratio, we have designed a custom charge amplifier. The amplifier is also built to minimize undesirable electrical loading on the drum. Finally, as the scale of this film is on the order of millimeters to tens of microns, MEMS fabrication technology is being evaluated for manufacturing the devices. So far, we have developed numerical and analytical models which have been verified through experimentation. These devices will be brought to a stage where they can be safely implanted in humans permanently.

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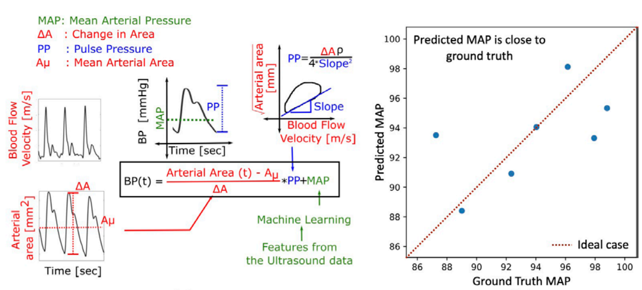
Research Interests:
Information processing, multimedia, quantum devices, systems, computer architecture, machine learning, quantum computing.

Absolute Blood Pressure Measurement using Machine Learning Algorithms on Ultrasound based Signals

6.02

H. Wang, A. Chandrasekhar, J. Seo, A. Aguirre, S. Han, C. G. Sodini, H.-S. Lee
Sponsorship: MIT J-Clinic, Philips, MIT-IBM Watson AI Lab, NSF CAREER Award, and DARPA SDH

Time-domain Blood Pressure (BP) waveform measurement has significant clinical values such as in Hypertension diagnosis. In an Intensive Care Unit (ICU), physicians use invasive radial catheters to measure BP from patients' radial artery, which is painful. We propose a non-painful way to get BP waveform with blood flow velocity and arterial area obtained from non-invasive ultrasound signals (a). In this process, we have to estimate the Mean Arterial Pressure (MAP). Hence, we propose to use a machine learning model containing 1D convolution and Transformer encoder layers to regress the MAP accurately. The convolution layers perform feature extractions, and Transformer models the relationship between time steps. We perform the training on the "PWDB" synthetic dataset and test on seven real patients. The model provides accurate results (b), with mean absolute error 2.6mmHg and std 2.1mmHg. Our algorithm has large potential to make affordable BP waveform measurements accessible to everyone.



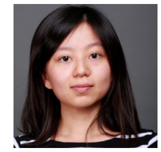
▲ (a) The whole pipeline of using machine learning-based algorithms to get blood pressure waveform from ultrasound data. (b) Predictions of the machine learning model is very accurate with mean absolute error 2.6mmHg and std 2.1mmHg.

Measuring Eye Movement Features using Portable Devices to Track Neurodegenerative Diseases

6.03

H.-Y. Lai, C. G. Sodini, T. Heldt, V. Sze

Sponsorship: MIT-IBM Watson AI Lab



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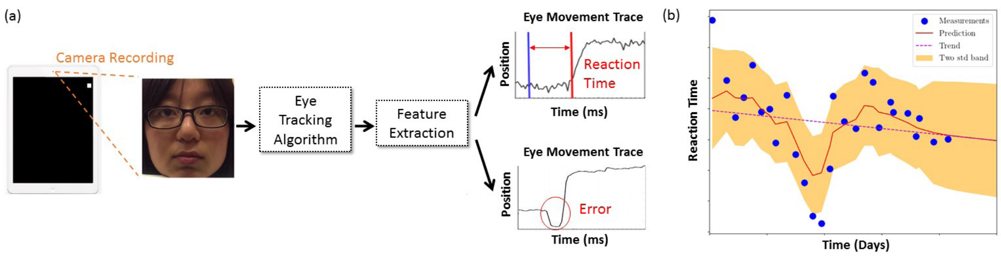
Research Interests:
Communications, information processing, multimedia, signal processing, data analysis/ inference, machine learning, optimization.

Current clinical assessment of neurodegenerative disease progression (e.g., Alzheimer's disease) is qualitative and time-consuming, which limits our ability to evaluate treatment response. Eye-movement features have been shown to be significantly different between patients and healthy subjects, suggesting their use as objective and easily-accessible metrics. However, these features are commonly measured with high-speed, IR-illuminated cameras. A portable measurement system is required to track them longitudinally.

Previously, we enabled ubiquitous tracking of eye-movement features by enabling app-based measurements of visual reaction time and error rates. In this work, we further show how we learn potential trends in these eye-movement features using Gaussian process modeling. We hope by comparing the trends of the features with the clinical assessments, we can evaluate the potential to use our system to track disease progression more frequently and widely than previously possible.



▲ (a) Our measurement system includes the tablet-based video recording, an eye tracking algorithm, and feature extraction algorithms. (b) Example reaction-time measurements from a subject and the trend learned from the data.

Analytical and Numerical Modeling of an Intracochlear Hydrophone for Fully Implantable Assistive Hearing Devices

6.04

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Sponsorship: NIH R01, NSF GRFP

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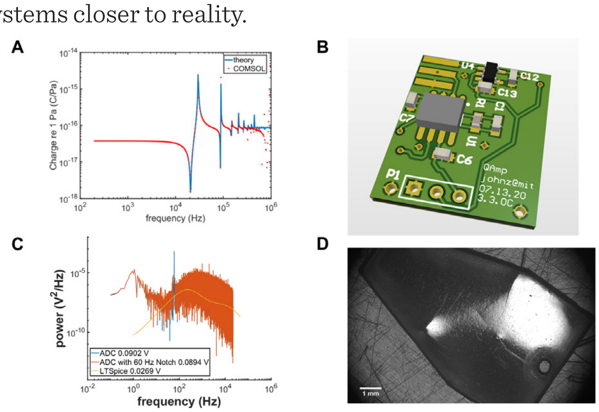
Research Interests:
Actuators, batteries, bioMEMS, communications, electronic devices, electronics, information processing, MEMS & NEMS, nanomanufacturing, nanomaterials, nanotechnology, quantum devices, sensors, transducers.

Cochlear implants with fully implantable microphones would allow for directional and focused hearing by taking advantage of ear mechanics. They would be usable in almost all environmental conditions throughout the day and night. Current implantable microphones suffer from unstable mechanics, poor signal-to-noise ratio (SNR), and low bandwidth.

In this work, we used analytical modeling, a finite element model, and experiments to design a polyvinylidene (PVDF) intracochlear hydrophone for high-bandwidth sensitivity, surgical viability, and improved SNR by electrical shielding and circuit design. Our analysis shows that the copolymer PVDF-TrFE should be used due to its higher hydrostatic sensitivity, area of the sensor should be maximized to maximize gain, and length should not exceed a maximal value determined by the bandwidth requirement. A short-circuit topology charge amplifier maximizes the SNR of the sensor by minimizing noise and attenuating electromagnetic interference by shielding. These advances in sensor performance bring fully implantable systems closer to reality.



◀ (a) Frequency response of the device predicted by theory and our finite element model, (b) four-layer charge amplifier PCB, (c) LTSpice and measured noise of the charge amplifier, and (d) laser cut PVDF-TrFE for sensing intracochlear pressure.

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Research Interests:
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Ultrasound-based Cerebral Arterial Blood Flow Measurement

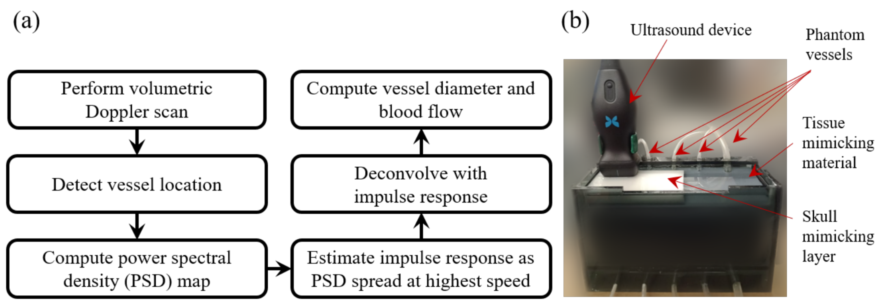
6.05

S. M. Imaduddin, T. Heldt

Sponsorship: Analog Devices Inc.

Ultrasound-based cerebral blood flow (CBF) monitoring is vital in the diagnosis and treatment of a variety of acute neurologic conditions. While flow velocity can be measured using Doppler ultrasound, accurate CBF measurement is difficult as vessel diameters cannot be determined reliably due to acoustic aberrations introduced by the skull and because cranial attenuation necessitates low frequency (1-2 MHz) insonation with poor spatial resolution.

We have developed a CBF estimation technique that achieves the spatial resolution required for CBF determination by estimating the point spread function of the imaging system. The received data are then deconvolved to increase spatial resolution, and a correction is applied to account for cranial aberrations. Doppler data were collected from phantom blood vessels with diameters between 2 and 6 mm over a 150 mL/min range using a clinical ultrasound device. Our method achieved an RMSE of 26 mL/min, within acceptable range for cerebral perfusion monitoring at the bedside.



▲ (a) Flow chart of proposed measurement technique, and (b) Flow phantom used to test our method.

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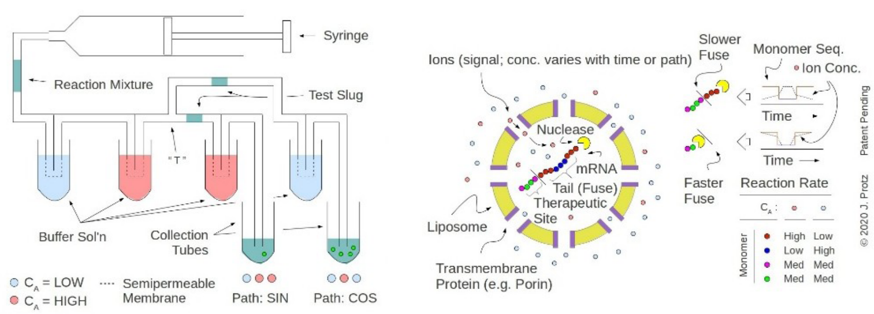
Bio-Nanoparticle for Drug Delivery Using TERCOM

6.06

J. Protz, M. Tanner, B. Vasievich, A. Lee, A. Jain, T. LaBean

Sponsorship: Protz Lab Group, BioMolecular Nanodevices LLC

Targeted drug delivery has been an area of active investigation for many decades. Some approaches target cell-borne receptors or use external stimuli to drive spatially-localized release. In this work, particles estimate their own location within the body by correlating their sensed fluid environment (e.g. temp., salinity, sugar, pH, ion conc., etc.) against an embodied map and release on the basis of this estimate; the approach is related to terrain contour matching (TERCOM), a technique used in air navigation. Current efforts focus on a reaction mixture contained within permeable vessels which synthesize a path-dependent dose of therapeutic while en route to a target site. An experimental apparatus has also been designed to test such synthesis. A parallel continuing line of effort explores polymers that exhibit path-dependent evolution of their conformation. The work builds on past efforts by the PI and his group to develop nanoparticles which record the trajectory of their environment. Progress may enable a new class of engineered pharmaceuticals.



▲ Illustration of concept: nuclease with environmental and substrate sensitivity consumes protective tail and reaches active therapeutic site faster when reaction mixture travels along non-target paths, causing larger dose of therapy to be delivered to target sites than to non-target sites.

Session 7: Electronic Devices

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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.

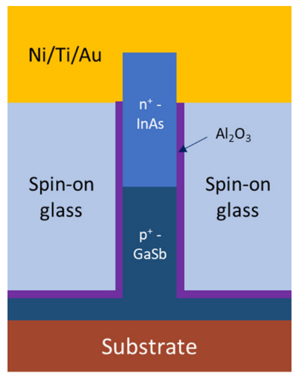
III-V Vertical Nanowire Esaki Diodes with Record-high Current Density

7.01

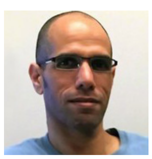
Y. Shao, J. A. del Alamo
Sponsorship: Intel

Tunnel field-effect transistors (TFETs) are promising logic devices for their capability to break the thermal limit of the subthreshold operation of MOSFETs. However, a long-lasting concern for TFETs is that the experimentally observed drive current is significantly lower than that of state-of-the-art MOSFETs. This prevents TFETs from meeting the performance targets for nanoscale CMOS.

Among TFET structures, the broken gap GaSb/InAs system is one of the most promising. Towards this goal, in this work, two-terminal GaSb/InAs vertical nanowire Esaki diodes are fabricated and characterized, with the smallest diameter being 10 nm. A record-high Esaki peak current density of 217 MA/cm2 is demonstrated, also showing good scaling behavior for diameter < 65 nm. A peak-to-valley current ratio (PVCR) of 3.4 is achieved. These results shed light on the potential of achieving high drive current in GaSb/InAs TFETs for future VLSI applications.



◀ Schematic of the vertical nanowire GaSb/InAs Esaki diode structure.



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Research Interests:
2D materials, biological devices and systems, electronic devices, electronics, energy, field-emitter devices, GaN, III-Vs.

The Mysterious Layer on Hydrogen Terminated Diamond Surface

7.02

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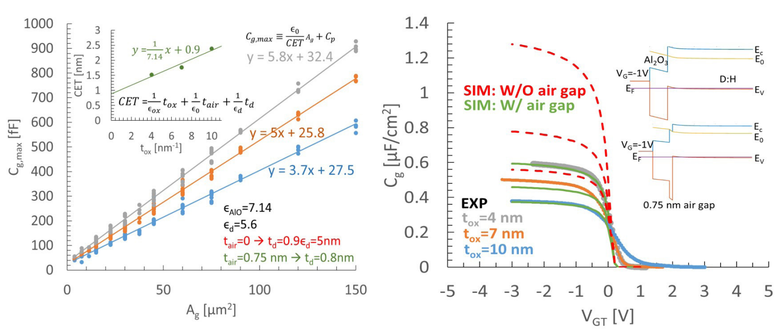
Sponsorship: U.S Israel BSF, Bose, DARPA

The surface conductivity of H-terminated diamond (D:H) is usually explained by the transfer doping model. The model assumes a surface dopant layer is formed on D:H surface that generates a two-dimensional hole gas (2DHG) in the diamond. The dopant layer is typically assumed to be of atomic dimensions. However, since the D:H surface is almost perfectly passivated, there are no chemical bonds out of the surface and the dopants are weakly held by van der Waals forces. Consequently, when analyzing the capacitance of MOSFETs built on D:H, the capacitance is much smaller than expected. To study the nature of this layer, we have analyzed the scaling properties of the gate capacitance of Al/Al2O3/D:H MOS structures. Our findings can be interpreted as suggesting the existence of an "air gap" of 0.5-1 nm in thickness at the Al2O3/D:H interface.



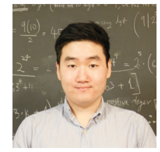
▲ (Left) scaling of gate capacitance with gate area for capacitors with different Al2O3 thickness (legend in right figure). From the slope of the lines, the capacitance equivalent thickness of air (CET), defined in the upper right corner, is extracted. Inset: CET vs. Al2O3 thickness; from the slope, the Al2O3 dielectric constant is extracted (7.1); the intercept is the semiconductor density of states capacitance found to be unrealistically small – as if the 2DHG extend td=5 nm into the diamond. Assuming tair=0.75 nm yields a more realistic td=0.8 nm. (Right) comparison of experimental CV data and P-S simulations with and without 0.75 nm "air gap".

Bias Temperature Instability Under Forward Bias Stress of Normally-Off GaN High Electron Mobility Transistors

7.03

E. S. Lee, J. A. del Alamo

Sponsorship: Texas Instruments



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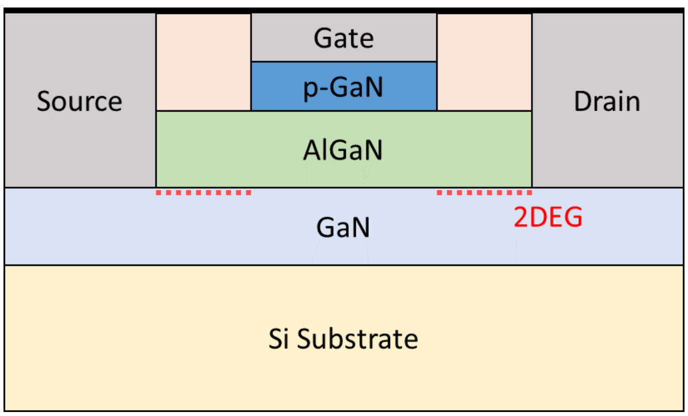
Research Interests:
Electronic devices, GaN, III-Vs, nanotechnology.

GaN field-effect transistors (FET) show great promise as energy efficient high-voltage power transistors. For best circuit reliability, safety and performance, a normally-off transistor is desirable. An attractive design is the p-doped GaN gate High Electron Mobility Transistor (p-GaN HEMT).

Our research aims to better understand the reliability issues impeding widespread adoption of p-GaN HEMTs. Here, we show that device degradation under forward-bias electrical stress, i.e. when the device is on, shows multiple regimes that are voltage and time dependent. Due to the more complex gate stack with a p-doped GaN layer, the devices show bias temperature instability (BTI) degradation with signature characteristics of electron and hole trapping. Furthermore, we show that some of the degradation is recoverable.

Altogether, our research reveals the presence of rich and dynamic degradation physics for the p-GaN HEMTs that must be well understood before the commercial success of this technology.



◀ Simplified cross section of the p-GaN gate HEMT. AlGaN/GaN interface naturally induces a 2-dimensional electron gas (2DEG) that allows for conduction. However, the addition of the p-GaN layer leads to a natural depletion of the 2DEG.

NbN-Gated GaN Transistor for Application in Quantum Computing Systems

7.04

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Sponsorship: IBM

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Research Interests:
2D materials, actuators, communications, electronic devices, electronics, energy harvesting devices and systems, GaN, III-Vs, integrated circuits, medical devices and systems.

High performance and scalable cryogenic electronics is an essential component of future quantum information systems, which typically operate below 4K. Superconducting qubits need advanced RF and pulse shaping electronics which typically occupies large instrumentation racks operating at room temperature. This approach is not scalable to the millions of qubits needed in future quantum systems.

This work explores the use of wide band gap heterostructure electronics, specifically the AlGaN/GaN high electron mobility transistor (HEMT), for cryogenic low-noise applications. These structures take advantage of the polarization-induced two-dimensional electron gas to create a high mobility channel, hence eliminating the heavy doping needed in the other semiconductor technologies. Epitaxially-grown GaN-on-Silicon wafers have been demonstrated in large (12 inch / 300 mm) substrates, therefore making the technology an excellent candidate for scalable RF electronics in quantum computing systems.

Furthermore, the use of electrodes using superconducting materials is proposed to significantly reduce the parasitic components and therefore push the RF performance of cryogenic devices. Short-channel transistors with NbN gates of length 250 nm have been demonstrated with promising performance.

In the next step, the effect of the superconducting gate on RF characteristics of the transistors will be studied, with the eventual goal of pushing the frequency performance of these transistors to new limits. These transistors will be integrated into low noise amplifier circuits for applications in readout and control electronics at cryogenic temperature. Furthermore, the demonstrated NbN-gated GaN transistor paves the way for the application of high frequency GaN technology in cryogenic electronics, notably in scalable quantum computing systems, and brings us one step closer to an all-nitride integrated electronics-quantum device platform.

CMOS-compatible Protonic Programmable Resistors

7.05

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Sponsorship: IBM

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2D materials, electronic devices, electronics, field-emitter devices, GaN, III-Vs, integrated circuits, nanomanufacturing, nanomaterials, nanotechnology, SiSiGe and Ge.

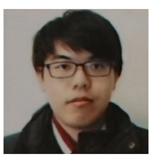
Programmable nonvolatile resistors are widely explored devices as building blocks for analog deep learning accelerators. Recently, devices that are programmed by ion intercalation were demonstrated to have superior modulation characteristics with respect to state-of-the-art phase change and filamentary resistive memories. Protonic devices are considered to be particularly promising since protons, the smallest cations, can be shuffled at higher speeds without causing mechanical deformation in the host materials. Previously, such protonic devices contained organic or polymer layers, which strictly limited the scalability, reproducibility, uniformity, yield, and CMOS-process integration of the technology. In this work, we show protonic programmable resistors consisting of a transition-metal-oxide channel (WO_3 or V_2O_5), P-doped SiO_2 electrolyte, and a Pd reservoir. We demonstrate reversible and nonvolatile conductance modulation by transferring protons between the channel and reservoir. We discuss material and device geometry optimization as well as the scaling trends in order to unlock the full potential of this new family of protonic resistive devices. This new device technology can satisfy the stringent requirements for analog crosspoint elements while using a fully CMOS-compatible and scalable fabrication flow.

Sharpened GaN Nanopyramids for Field Emission Applications

7.06

P-C. Shih, T. Palacios

Sponsorship: MURI/AFOSR



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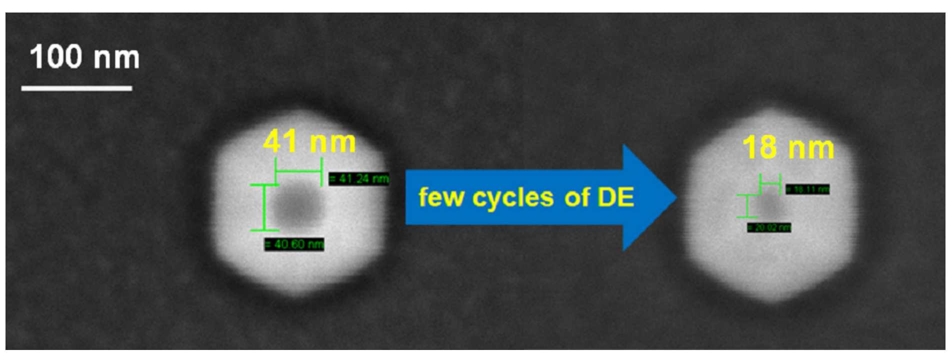
Research Interests:
2D materials, electronic devices, electronics, energy harvesting devices & systems, field-emitter devices, GaN, III-Vs, lasers, light-emitting diodes, nanomanufacturing, nanotechnology, optoelectronics, photonics, photovoltaics.

Field emitters, also known as vacuum transistors, are promising for harsh-environment and high-frequency electronics. Despite their great potential, high operation voltage and stability still needs improvement. III-Nitrides could overcome these issues thanks to tunable electron affinity and large bonding energy. At the 2020 Device Research Conference, we demonstrated the first GaN field emitters with a self-aligned gate with a sub-30 V turn-on behavior. More recently, to further reduce the operation voltage, a novel digital etching technology has been developed to sharpen the emitter tips from 40 nm down to below 20 nm.



▲ (a) Top-view and (b) side-view of SEM images of GaN Nanopyramids. The tip is sharpened by digital etching (DE).

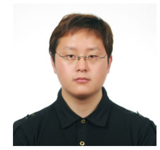
Investigation of Trap Properties in Sub 10nm FW InGaAs FinFETs for Expecting Future Devices

J. S. Kim, A. Vardi, J. A. del Alamo

7.07

Semiconductor devices have been continuously scaled from its birth. As the result, current state-of-the-art devices reach a few nm sizes. Modern small sized devices are under quantum mechanical effects such as sub-band by energy quantization and volume inversion. Although some devices used the effects actively, those new arise effects should be considered to develop emerging devices.

In this work, we studied trap properties of HfO2/In0.7Ga0.3As FinFETs by changing its fin width (FW: 7~25 nm). The trap density in the FinFETs can be measured by comparing DC and RF-Id measurement. The RF-Id can measure properties of transistors without trap effects by using over GHz frequency comparing DC-IV measure device properties with trap effects. From the results, sub 10-nm FW FinFET showed relatively small trap density due to worse injection conditions. However, its highly quantized level induces access to high energy traps. This effect should be considered for extremely small sized transistors.



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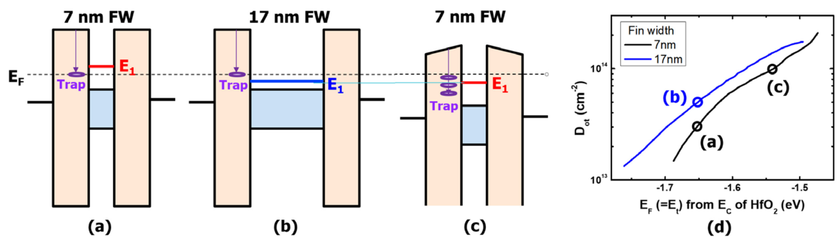
Research Interests:
Electronic devices, III-Vs, nanotechnology, quantum devices, Si, reliability.



▲ Energy bands of (a) 7 nm and (b) 17 nm FinFETs in same EF condition. (b) and (c) are in similar carrier concentration (EF-E1 are similar in both cases). (d) Measured trap densities of 7 and 17 nm FinFETs. (a)-(c) conditions are marked in figure (d).

CMOS SPADs in 55nm BCDLite Platform

J. Kim, A. Mestre, J. Xue, D. Chong, K. M. Tan, H. Nong, K. Y. Lim, D. Gray, D. Kramnik, A.Atabaki, E. Quek, R. J. Ram

7.08

Sponsorship: Kwanjeong Educational Foundation and Global Foundries

Single photon avalanche diodes (SPAD) are a promising class of sensing devices for myriad applications ranging from biomedical imaging, consumer electronics, to quantum computation. SPADs fabricated in CMOS processes enjoy the benefits of integrated high-speed electronics which enable arrays of detectors and improvements in dynamic range. However, integrated SPAD devices realized in sub-100nm CMOS processes have historically had lower performance compared to devices fabricated in more mature processes (130 nm and older). In this paper we report a high performance SPAD devices fabricated in a 55nm BCD process with 24.7% photon detection probability (PDP) at 650nm, dark count rate (DCR) of 44.7 cps/μm2, when biased at 8% excess bias. An integrated quenching circuit was fabricated which achieved a saturation count rate of 11.8 Mcps. This result demonstrates the unique capability of the BCDLite platform which is a variant of a Bipolar-CMOS-DMOS process with its diverse dopant options to realize high performance SPAD devices alongside high-voltage electronics and advanced logic circuitry.

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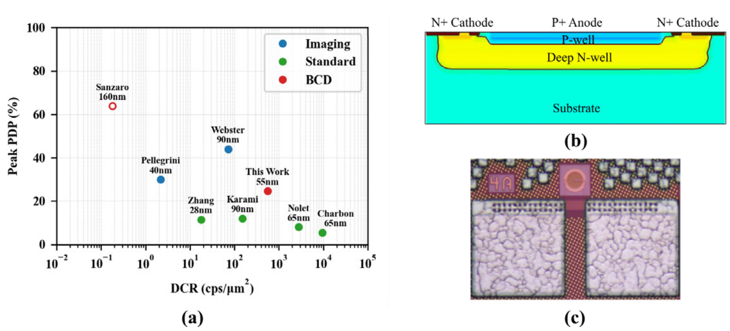
Research Interests:
2D materials, biological devices & systems, bioMEMS, integrated circuits, light-emitting diodes, medical devices & systems, MEMS & NEMS, microfluidic devices & systems, nanomanufacturing



▲ (a) DCR vs Peak PDP plot of integrated CMOS SPADs reported in literature, (b) Junction cross-section, and (c) Micrograph of CMOS SPAD device.

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Research Interests:
Electronic devices, electronics, field-emitter devices, MEMS and NEMS, nanomaterials, nanotechnology, sensors.

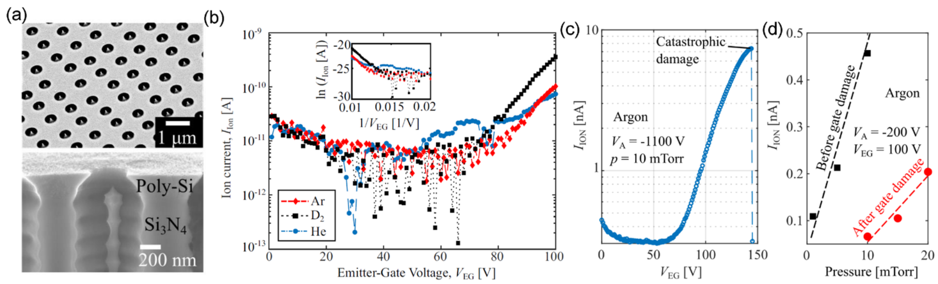
Low Voltage Gated-Si Field Ionization Arrays

7.09

G. Rughoobur, A. Sahagun, O.O. Ilori, A.I. Akinwande

Sponsorship: DARPA (HR0011-15-20012)

Field ionizers are promising for applications such as neutron imaging. Field ionization (FI) consists of a valence electron from a gas atom or molecule tunneling across a potential barrier, into a vacant electron state in a pointed electrode – an “ionizer”. However, ion sources based on FI require extremely high positive electric fields, of the order of 10 V·nm-1. In this work highly scalable and compact Si field ionization arrays (FIAs) with a unique device architecture that uses self-aligned gates and a high-aspect-ratio (~50:1) silicon nanowire current limiter are demonstrated. The tip radius of ~5 nm and gate aperture diameter of ~350 nm enables field factors, β, > 1 × 106 cm-1. With these Si FIAs, gate-emitter voltages of <200 V are shown to achieve ion currents in the nA range at pressures ~10 mTorr for high ionization energy gases such as Ar, He and D2. In addition, we demonstrate that vacant surface states are responsible for minimum ionization energies lower than 100 V.



▲ (a) Electron micrographs of the tip and array, (b) Ion current for different gases in the low field regime, (c) Maximum current observed with Ar before damage and (d) Ion current with pressure before and after gate damage.

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Biological devices and systems, bioMEMS, medical devices and systems, microfluidic devices and systems.

Rethinking Plant-based Materials Production: Selective Growth of Tunable Materials via Cell Culture

8.01

A. L. Beckwith, J. T. Borenstein, L. F. Velásquez-García

Sponsorship: Sponsored in part by the Draper Fellowship Program

Current systems for plant-based materials production are inefficient and place unsustainable demands on environmental resources. Traditionally cultivated crops present low yields of industrially useful components and require extensive post-harvest processing to remove extraneous portions of the plants. Large-scale monoculture remains the unchallenged standard for biomass production despite negative impacts of the practice to the surrounding biome as well as a susceptibility to season, climate, and local resource availability. This work proposes a novel solution to these shortcomings based on the selective cultivation of useful, tunable plant tissues using scalable, land-free techniques. By limiting biomass cultivation to only desirable plant tissues, ex planta farming promises to improve yields while reducing plant waste and competition for arable land.

Employing a Zinnia elegans model system, we provide the first proof-of-concept demonstration of isolated, tissue-like plant material production by way of gel-mediated cell culture. Parameters governing cell development and morphology including hormone concentrations, medium pH, and initial cell density are optimized and implemented to demonstrate the tunability of cultured biomaterials at cellular and macroscopic scales. Targeted deposition of cell-doped, nutrient-rich gel scaffolds via injection molding and 3D bioprinting enable biomaterial growth in near-final form, reducing downstream processing requirements. These investigations demonstrate the implementation of plant cell culture in a new application space, propose novel methods for quantification and evaluation of cell development, and characterize morphological developments in response to critical culture parameters—illustrating the feasibility and potential of the proposed techniques.

The proposed concept of selectively-grown, tunable plant materials via gel-mediated cell culture is believed to be the first of its kind. This work uniquely quantifies and modulates cell development of cultured primary plant products to optimize and direct growth of plant materials.

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Research Interests:
Information processing, machine learning for time series in manufacturing.

NonlinearTime Series Regression with Autocorrelated Error using Neural Networks

8.02

F.-K. Sun, D. S. Boning

Sponsorship: Lam Research

Time series data is ubiquitous. Researchers in many fields, including social sciences, operations research, and engineering, often collect time series data to create models for systems without prior or precise knowledge of model structure and in turn, provide insight for such systems. During this process of collection and creation, errors inevitably occur. Usually, the assumption is that the errors are uncorrelated at different time steps. However, in practice, errors can be autocorrelated when (1) the function space of the model and the true underlying system does not intersect, (2) some key explanatory variables are not collected, or (3) a measurement error at a current time step can carry over to future time steps.

To solve this issue, previous literature, such as the Cochrane–Orcutt estimation, only focuses on cases where the model is linear or only contains predefined nonlinearity. This greatly limits its usage, as many systems today (such as semiconductor manufacturing) is almost certainly nonlinear while the underlying nonlinearity is unknown.

Here, we propose to use neural networks (NNs) to approximate the unknown nonlinearity and adopt an adjusted procedure to the Cochrane–Orcutt estimation. The input to our model is a vector of features at time t and the output is the target scalar. This enables us to train a NN that can fit the nonlinearity and adjust correspondingly to its autocorrelated noise. Compared to previous methods, we have the advantages of (1) fitting unknown nonlinearity with autocorrelated noise and (2) updating autocorrelation coefficient according to validation error. Our experimental results show that we are able to separate the autocorrelated noise from the nonlinear data and thus achieve better testing error.

Low-Temperature Growth of High Quality MoS2 by Metal-Organic Chemical Vapor Deposition

8.03

J.-H. Park, A.-Y. Lu, P.-C. Shen, J. Kong

Sponsorship: ARO MIT-ISN, Center for Energy Efficient Electronics Science

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Research Interests:
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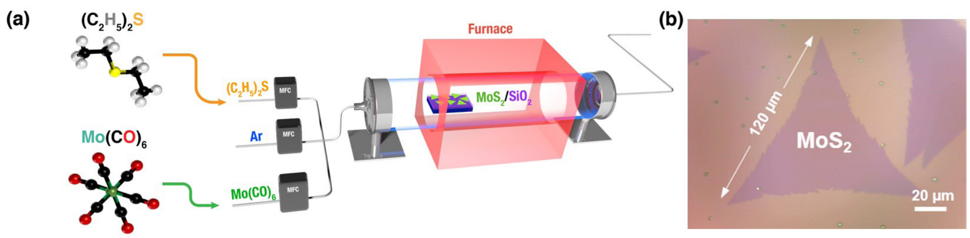
High-quality molybdenum disulfide (MoS2) synthesis plays an important role in realizing industrial applications of flexible and ultimately scaled devices due to its atomically thickness. However, current techniques for chemical vapor deposition (CVD)-grown MoS2 require a high synthetic temperature and a transfer process, which limits its utilization in device fabrications. In this work, we achieved the direct synthesis of high-quality monolayer MoS2 with the domain size up to 120 µm by metal-organic chemical vapor deposition (MOCVD) at a temperature of 320 oC. Owing to the low substrate temperature, the MOCVD-grown MoS2 exhibits low impurity doping and nearly unstrained properties, demonstrating enhanced electronic performance with high electron mobility of 68.3 cm2 V-1s-1 at room temperature. In addition, by tuning the precursor ratio, we develop a better understanding of the MoS2 growth process, which can provide further guidance for the synthesis of 2D materials.



▲ (a) Schematic diagram of the experimental setup of the MOCVD system for MoS2 growth and (b) Optical image of MoS2 flake grown on silicon oxide substrate at low temperature of 320 oC.

Dipole Doping of Ultra-wide Bandgap 2D Materials

8.04

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Sponsorship: SRC

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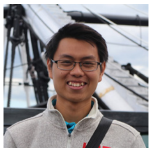
Research Interests:
2D materials, electronic devices, energy harvesting devices & systems, GaN, III-Vs, nanomaterials, nanotechnology, SiGe and Ge.

Among all the possible back-end-of-line (BEOL) solutions to improve the integration density and functionality of conventional silicon circuits, 2D material devices are very promising, due to their high mobility, relatively large band gaps, and atom-level thickness. These devices are beneficial for both logic integrated circuits and power electronic applications. However, controllable doping of 2D materials and achieving low contact resistance have always been challenging and hinder the development of 2D material devices and circuits.

Recently, we have fabricated back-gated Bilayer MoS2 transistors with vertical MoSSe/MoS2 structure in the source drain region. The Janus 2D material, MoSSe would function as a vertical dipole layer due to its built-in structural cross-plane asymmetry, which modulates the work function of the source/drain contacts above and the fermi level of the underneath MoS2 in the source/drain region. Accordingly, the Schottky barrier formed between the metal contacts and MoS2 would be lowered and the on-state current of the MoS2 transistor would be improved accordingly. We have experimentally observed a five-time current increase in devices with the Janus source/drain region, compared with bilayer MoS2 transistors using similar metal contacts. Such dipole doping method can also be applied to reduce contact resistance and to realize localized doping in other 2D material systems.



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Research Interests:
Electronic devices, nanotechnology, photonics, quantum devices, spintronics.

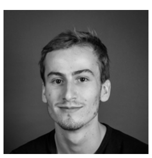
Polarization Switching of Metal/Hf0.5Zr0.5O2/Si Capacitors

8.05

K. Limanta, A. Zubair, N. S. Rajput, T. Palacios
Sponsorship: MIT EECS - Advanced Micro Devices Undergraduate Research and Innovation Scholar

Ferroelectric materials exhibit spontaneous and electrically switchable non-volatile polarization which is promising for a wide variety of applications such as non-volatile ferroelectric memories (FeRAM), high-k gate-dielectric for CMOS transistors, negative capacitance effect transistors, photodetectors, and piezoelectric actuators. Recently, ferroelectric materials have also shown promises for machine learning (i.e. analog synapses, coupled oscillator networks, spiking neurons, etc.) and quantum computing applications (i.e. cryogenic memory). The application of conventional lead zirconate titanate type ferroelectric suffers from scalability and lack of CMOS compatibility. However, the high-k dielectric HfO2 when doped with Zr, Al, Si, etc. and annealed at high (~500°C) temperature exhibits ferroelectricity down to a few nm, opening up a path for the realization of CMOS-compatible emerging applications using ferroelectric materials.

In this project, we demonstrate wafer-scale CMOS compatible Zr-doped HfO2 with robust ferroelectric properties down to 5 nm thickness. We fabricate metal-ferroelectric-metal (MFM) and metal-oxide-semiconductor (MOS) capacitors on Si wafers using a standard CMOS process flow to evaluate the performance of ferroelectric films. A ferroelectric MOS capacitor is the key building block for all of the above-mentioned electronic applications. To understand the polarization switching behavior as a function of annealing temperature, we characterize the capacitors using small-signal capacitance-voltage, large signal pulse measurements, and DC I-V measurements. Our study reveals the presence of robust ferroelectricity in the fabricated capacitors when annealed at 400°C and paves the way for the development of emerging electronic applications of ferroelectric materials compatible with back-end-of-the-line CMOS process flow.



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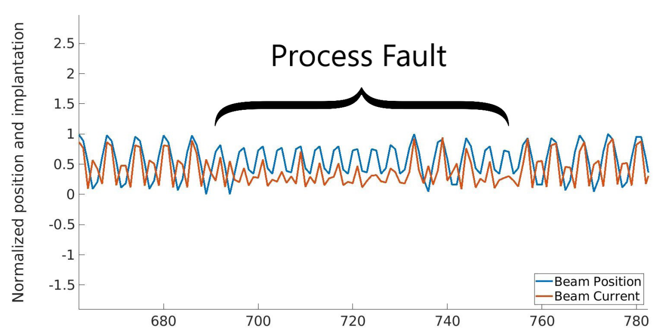
Research Interests:
Information processing, molecular & polymeric materials, nanomanufacturing, machine learning, pattern dependent variations, spin coating, electro chemical plating, process modelling.

Fault Detection for Semiconductor Processes Using One Class Parzen Window Classifiers

8.06

C. Lang
Sponsorship: Analog Devices, Inc.

Faults in fabrication processes are extremely costly. When undetected and unaddressed, they will continue to ruin wafer lots until the underlying problem is corrected, leading to massive yield losses. Our work uses one-class Parzen window classifiers to raise alerts when faults are suspected by monitoring process sensor information, reducing future yield loss. These models are kernel based density estimation methods which determine the similarity of incoming data to known good process data. The method uses only nominal process data which is desirable as faults are often unique, and examples will not be available before they occur. Using historical examples of a wide variety of faults in plasma etch and ion implantation processes (Fig. 1), our fault detection methodology captures more than 90% of faults, with a false positive rate of less than 0.5%. This method can be applied to a wide variety of processes without significant adjustment, making it ideal for generalized fault detection.



▲ Example fault in the ion implantation process causing yield losses. Within the faulty segment, beam current is lower than expected, and does not follow the nominal pattern as seen outside this range.

Bilayer Graphene in Frank van der Merwe Growth and its Machine-learning-assisted Characterization

8.07

H. Wang, Z.Yao, G. S. Jung, Q. Song, M. Hempel, T. Palacios, G. Chen, M. J. Buehler, A. Aspuru-Guzik, J. Kong

Sponsorship: NSF Award No. 0939514

Bilayer graphene is now a rising star for the discoveries of unconventional physics. While the number of exciting physical phenomena observed in bilayer graphene increases, a big gap persists in transforming these discoveries into useful applications, owing to the small-scale samples obtained via top-down approach. We realized a layer-by-layer (that is, Frank-van der Merwe) growth mode in large-scale bilayer graphene, with no island impurities, which is unprecedented in any van der Waals-stacked materials. This is important because it ensures the purity, quality and homogeneity of any thin films. Owing to counter-intuitive growth principle in chemical vapor deposition graphene, we proposed a new physical quantity, named "interface adhesive energy", that can be used to predict the growth mode. We show, through first-principle calculations, this new physical quantity is tunable. We have thus realized the classical Frank-van der Merwe growth mode in graphene.

The characterization of graphene is a historical problem. Since the first report of graphene, researchers have been showing a few characterization images and spectrum of a material, based on random sampling. The situation became ambiguous for large-scale sample, when massive data involved. We have invented a machine-learning-assisted Raman analysis tool for precise characterization of stacking order and layer number of our graphene grown in Frank van der Merwe mode.

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Research Interests:
2D materials, electronic devices, electronics, nanomaterials, nanotechnology, photonics.

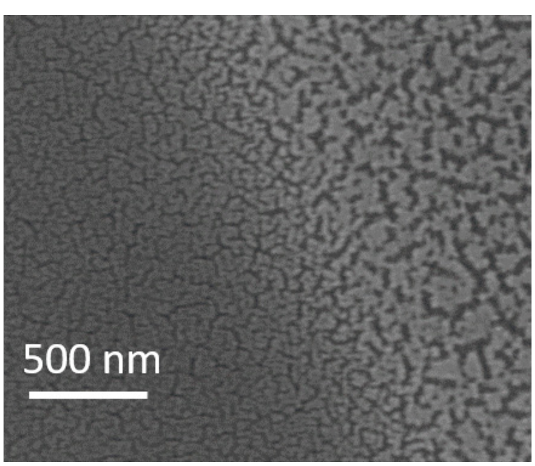
Adhesion in Nanoparticle-Enhanced Microsputtered Gold Thin Films

8.07

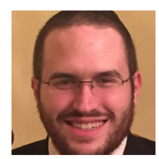
Y. Kornbluth, R. Mathews, L. Paramswaran, L. Racz, L.F. Velásquez-García

Sponsorship: U.S. Air Force

Silicon and gold are workhorses of CMOS and the microelectronics industry, but the physical interface between the two is lacking. Gold films do not adhere well to silicon, necessitating the need for an adhesion layer, often made of a third material. We show that if the gold film is sputtered in an atmospheric-pressure microsputterer, in the presence of a fast-moving jet of air, gold nanoparticles form. The high collisionality of the atmospheric-pressure gas and high energy of the plasma facilitate nanoparticle formation, while the jet carries the nanoparticles to the substrate. The nanoparticles then act as an adhesion layer to allow a gold film, made of these nanoparticles and individual atoms, to adhere well to a silicon or silicon dioxide substrate. By rastering the printhead over the desired deposition area, adhesion, density, and conductivity can be optimized simultaneously. Conductivity of the resultant films is also near-bulk, allowing for their use in microelectronics.



◀ SEM micrograph of film, with (right) and without (left) nanoparticles. While the left film is visibly more porous, the nanoparticles improve adhesion. Rastering the printhead overlays the density of the right film on the adhesive left film.



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2D materials, electronic devices, MEMS & NEMS, microfluidic devices & systems, nanomanufacturing, nanotechnology.

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Large Scale 2D Perovskite/Transition Metal Dichalcogenide Heterostructure for Photodetector

8.09

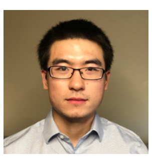
D. Lee, S. Bae, J. Kim

Sponsorship: SUSTECH

Monolayer transition metal dichalcogenides (TMDC) have been attractive nanomaterials for optoelectronics due to their extremely high quantum efficiency, but their atomically thin thickness prevent them from absorbing sufficient light for optoelectrical applications.

To improve optoelectrical performance of TMDC, during the past years, 2D Ruddlesden-Popper perovskites (PVSK)/TMDC heterostructures have been demonstrated. Thanks to their high absorption coefficient, long diffusion length of charge carrier, sharp exciton emission, and high power conversion efficiency, 2D PVSK have been used as an absorption layer for TMDC. However, 2D PVSK/TMDC heterostructures are limited in the micrometer scale, since 2D PVSK only have been fabricated by the tape-exfoliation method.

We reported Layer Resolved Splitting (LRS) technique to isolate multilayer 2D materials into monolayer in wafer scale in 2018. To improve scalability of 2D PVSK for large scale application, in this work, we successfully split micrometer-thick 2D PVSK into nanometer-thick scale with LRS technique. Then we also demonstrated large-scale 2D PVSK/TMDC heterostructure for photodetector, which only has been previously demonstrated up to micrometer scale.



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Integrated circuits, photonics, numerical method, machine learning.

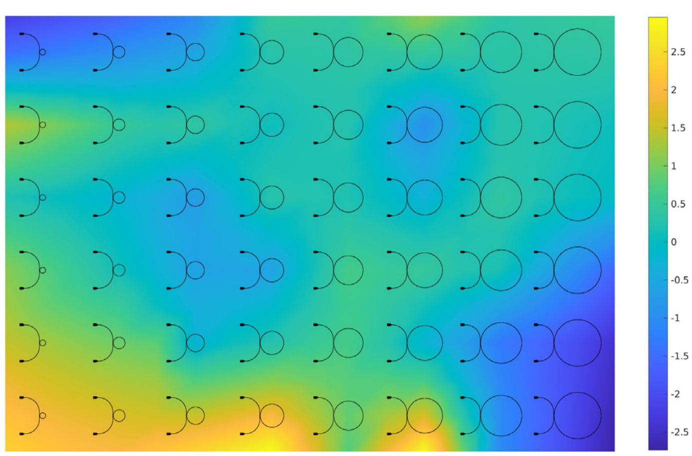
Inference of Process Variations in Silicon Photonics from Characterization Measurements

8.10

Z. Zhang, S. I. El-Henawy, C. Ríos, D. S. Boning

Integrated silicon photonics (SiP) provides great opportunities for various applications as a design platform that adopts existing CMOS fabrication infrastructure. However, understanding the process variations (PV) in SiP manufacturing and their impact remains challenging. To achieve the goal of industry-level manufacturing, one of the key steps is to find the distribution map of PV in the actual fabrication, which is usually inferred from well-designed test structure measurements.

In this work, we develop a Bayesian-based method to infer the distribution of systematic geometric variations in SiP. We apply this method to characterization data from multiple silicon nitride ring resonators with different design parameters. Our results show that this characterization scheme can serve as a good test structure for PV inference, which provides an alternative and efficient approach to study PV in SiP, and thus facilitates the design of high-yield SiP circuits in the future.



◀ The characterization design layout with our estimation of the thickness variation map inferred from the measurement.

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Electrically Reconfigurable Nonvolatile Metasurfaces based on Optical Phase Change Materials

9.01

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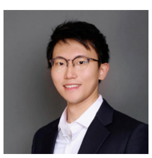
Sponsorship: DARPA EXTREME program (HR00111720029)

Active flat optics, especially active metasurfaces, promises reconfigurable optics with improved compactness, manufacturability, and tunability compared to their bulk counterparts. The unique nonvolatile switching capability of chalcogenide phase change materials (PCMs) makes them highly attractive for active metasurface applications. However, so far reversible phase transition in PCM-based optical devices are largely realized via either laser pulsing or electrical-current triggered transition. Both methods require raster-scanned writing and dedicated off-chip switching instruments, making them incompatible with on-chip integration. A robust and scalable on-chip PCM switching technique is thus highly demanded.

Here we report a scalable electrical switching method employing geometrically optimized on-chip integrated micro-heaters, enabling large-area reversible electrothermal switching for PCM-based metasurfaces. Based on this platform, we are able to achieve a reconfigurable bi-state spectral filter with a large contrast of over 400%. We also demonstrate continuously tunable active metasurfaces with a record high half-octave spectral tuning range. We further demonstrate a polarization-insensitive metasurface for active optical beam-steering.



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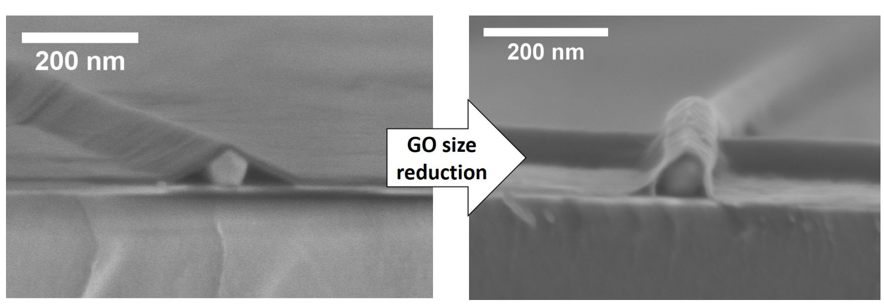
Research Interests:
2D materials, displays, electronic devices, energy, energy harvesting devices & systems, integrated circuits, light-emitting diodes, nanomanufacturing, nanomaterials, optoelectronics, organic materials, photovoltaics, si.

Conformally Encapsulated Silver Nanowires (AgNW) by Size-tuned Graphene Oxide Layers

9.02

W. H. Chae, J. J. Patil, T. Sannicolo, J. C. Grossman
Sponsorship: Equinor ASA

Silver nanowire (AgNW) networks are scalable alternatives to indium tin oxide as transparent electrodes for many applications such as solar cells or transparent heaters. However, AgNWs are prone to sulfidation and spheroidization due to instabilities at high temperatures, limiting widespread use. To improve their resilience, bare AgNWs usually require costly encapsulation processes to achieve a conformal coating. In this work, size-tuned graphene oxide (GO) was explored as an economical solution-based protective barrier material for AgNWs. Probe sonication reduced the lateral size of GO to submicron dimensions and subsequent layer-by-layer deposition was shown to create a conformal coating with nanoscale thickness tunability. The conformally coated AgNWs demonstrated enhanced chemical and electrothermal stability. Our encapsulation approach using GO could potentially be expanded to include other 2-dimensional materials to attain functional coatings of nanoscale structures.



▲ (Left) Cross-sectional scanning electron microscope (SEM) image of GO-coated AgNW before size reduction. (Right) Cross-sectional SEM of Size-tuned GO-coated AgNW, demonstrating improved GO conformality.

Dynamics of $HfZrO_2$ Ferroelectric Structures: Experiments and Models

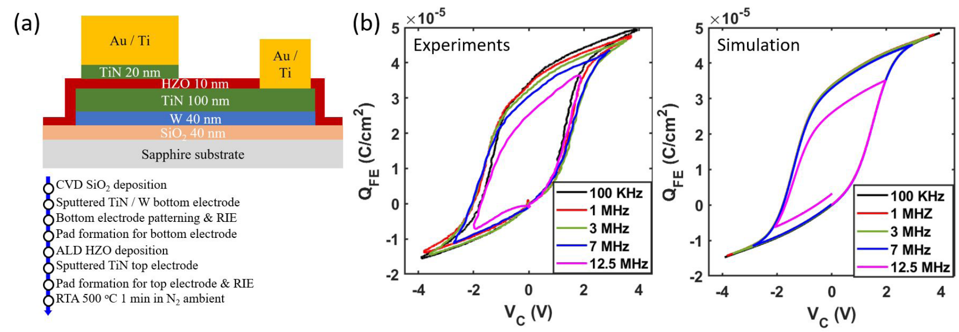
9.03

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

Sponsorship: Semiconductor Research Corporation and Samsung Electronics

Ferroelectric $HfZrO_2$ (FE-HZO) has attracted enormous interest in various semiconductor device areas, such as logic applications, memory devices, and analog computing. Among them, the negative capacitance (NC) effect transistor by incorporating a FE-HZO layer in the gate stack of a MOSFET has been studied to overcome the CMOS scaling limit. However, NC and FE dynamics of FE-HZO are still contentious and unclear.

In this work, we have investigated the dynamics of the Metal-FE-Metal (MFM) and Metal-FE-Insulator-Metal (MFIM) structures by calibrating and minimizing circuit and sample parasitics. In MFM structures, our new dynamic model based on the Preisach model describes well all observed behavior in a wide range of conditions. In MFIM structures, we observed clear NC behavior, which follows the Landau-Khalatnikov equation depending on the direction of the voltage drive vs. time. Our research contributes new understanding to the NC operation.



▲ (a) Schematic and fabrication process flow of FE-HZO MFM structure with low parasitics. (b) Comparison of Q-VC characteristics between experiment (left) and model prediction (right).

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2D materials, displays, electronic devices, electronics, III-Vs, integrated circuits, nanomanufacturing, nanomaterials, nanotechnology, Si, thermal structures, devices & systems.

Ultra-stable Supramolecular Nanostructures with Tunable Surface Chemistries from a Novel Aramid Amphiphile Platform

9.04

T. Christoff-Tempesta, J. Ortony

Sponsorship: NSF (CHE-194550), Professor Amar G. Bose Research Grant Program, Abdul Latif Jameel Water and Food Systems Lab, National Science Foundation Graduate Research Fellowship (1122374), and Martin Family Society of Fellows for Sustainability.

Aqueous self-assembly of amphiphilic small molecules is a recognized pathway to producing high surface area nanostructures with defined internal order. These nanostructures present tunable surfaces for designed interaction with their environment, offering new strategies for applications in environmental remediation, energy transport, and biomimetic grafts. However, these nanostructures commonly exhibit a range of dynamic instabilities, including molecular migration, rearrangement, and exchange, resulting from limited intermolecular cohesion within the nanostructures. In this work, we introduce a small molecule platform, the aramid amphiphile (AA), that is readily synthesized from established peptide coupling reactions. AAs incorporate a structural domain with dense intermolecular interactions into the hydrophobic core of the assembled nanostructure. The design characteristics of AAs elicit their self-assembly into microns-long planar nanoribbons with suppressed molecular exchange between assemblies. We show that AA nanoribbons exhibit a tensile strength of 1.9 GPa and Young's modulus of 1.7 GPa, providing sufficient mechanical stability for translation to the solid-state. We utilize an aqueous shear alignment process to form macroscopic threads from AA nanoribbons that are easily handled and support 200 times their weight when dried. The AA platform offers a novel route to extend small molecule self-assembly to aligned macroscopic materials and beyond solvated environments.

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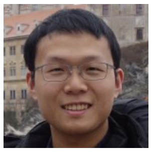
Molecular & polymeric materials, nanomaterials, nanotechnology, organic materials.



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Research Interests:
2D materials, electronic devices, information processing, nanomanufacturing, nanotechnology, quantum devices, spintronics.

Gigahertz Frequency Antiferromagnetic Resonance and Strong Magnon-Magnon Coupling in the Layered Crystal $CrCl_3$

9.05

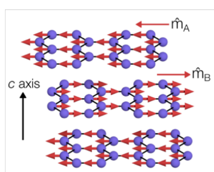
J. T. Hou, D. MacNeill, D. R. Klein, P.. Zhang, P. Jarillo-Herrero, and L. Liu

Sponsorship: DOE Office of Science (DE-SC0018935), Gordon and Betty Moore Foundation (GBMF4541), NSF (DMR-1231319, ECCS-1808826), and NSF Graduate Research Fellowship Program (1122374)

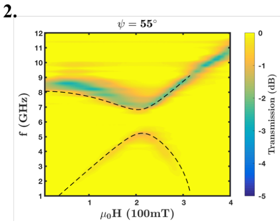
Magnon-magnon hybrid systems have recently been realized between two adjacent magnetic layers, with potential applications to hybrid quantum systems and coherent information processing. To realize magnon-magnon coupling within a single material, antiferromagnetic or ferrimagnetic materials with magnetic sublattice structures are required. However, conventional antiferromagnetic (AFM) resonance lie in THz frequencies which require specialized techniques to probe.

In this work, we realize strong magnon-magnon coupling within a single material, $CrCl_3$. $CrCl_3$ is a layered van der Waals AFM material, with parallel intralayer alignment and antiparallel interlayer alignment of magnetic moments (Fig.1). Because of weak anisotropy and interlayer magnetic coupling, we observe both optical and acoustic modes of AFM resonances within the range of typical microwave electronics (<20GHz), in contrast to conventional AFM resonances. By breaking rotational symmetry, we further show that strong magnon-magnon coupling with large tunable gaps can be realized between the two resonant modes (Fig.2). Our results demonstrate strong magnon-magnon coupling within a single material and establish $CrCl_3$ as a convenient platform for studying AFM dynamics in microwave frequencies. Because $CrCl_3$ is a van del Waals material which can be cleaved to produce air-stable monolayer thin films, these results open up the possibility to realize magnon-magnon coupling in magnetic van der Waals heterostructures by symmetry engineering.

1.



2.



◀ Figure 1: Magnetic structure of bulk CrCl3 below the Neel temperature. Blue spheres represent chromium atoms. Figure 2: Strong magnon-magnon coupling realized with magnetic field applied at an angle 55o with respect to the crystal plane.

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Research Interests:
Actuators, sensors, systems, thermal structures, devices & systems, artificial intelligence, machine learning, simulation.

Design Using Genetic Algorithms of Microchannels in a Cold-plate

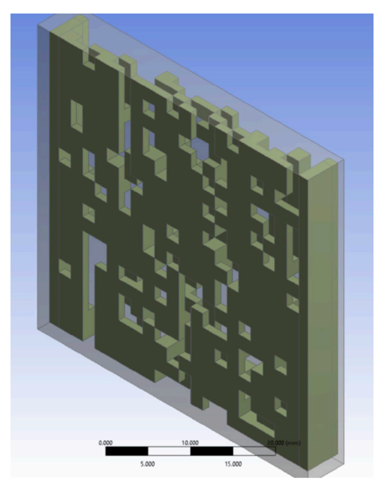
9.06

J. Izquierdo-Reyes, L.F. Velásquez-García

Sponsorship: MIT-Tecnologico de Monterrey Nanotechnology Program

Generative design is a technique in which the user provides a genetic algorithm (GA) with a restricted space and conditions. These algorithms design over several iterations to maximize or minimize certain device features. The resultant structures are of a complexity that is near impossible for a human to design. This project applies generative design to the microchannels of a cold plate. Generative design is ideal for creating modern devices since it can optimize spaces, shapes, and other features, leveraging advances in simulation software that can numerically evaluate complex designs. Additionally, the ability to pair with and design for new manufacturing methods such as additive manufacturing makes it a promising solution for future optimal designs.

Our goal was to reduce the temperature while maintaining reasonable pressure in our cold-plate. Results show that it is possible to improve thermal performance; however, the reduced space is a limiting feature. Larger voxels substantially reduce the computational cost but limit the possible resultant designs. Despite some success with this algorithm, it relies significantly on the user. Proper selection of the fitness function and the parameters of the seed design depend on the user's understanding of the problem's physics. Thus, we call for further exploration of methods for selecting starting points based on numerical factors rather than expertise.



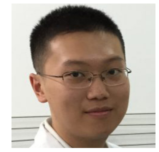
▶ Figure 1: Resultant cold-plate designed by a GA

Gated Nonreciprocal Magnon Transmission from Direction-dependent Magnetic Damping

J. Han, Y. Fan, B. C. McGoldrick, J. Finley, J. T. Hou, P. Zhang, L. Liu

Sponsorship: NSF, SRC, NIST

9.07



An important application of magnetic materials in information technology is to provide nonreciprocity, which allows unidirectional signal transmission. A representative device is the two-terminal microwave isolator. A ferromagnet inside naturally breaks the time-reversal symmetry and only allows microwave transmission from port 1 to port 2, while signals from port 2 to port 1 are suppressed. Despite wide applications, these conventional nonreciprocal devices suffer from their bulk volume and the difficulty of being integrated into high-density circuits. Nowadays, new mechanisms that can provide passive and directional isolation of signals are being pursued at sub-micrometer scale. Among various proposals, magnons, the quanta of the collective excitation of magnetic moments, show unique potential due to the tunability and the possibility for on-chip integration. So far, nonreciprocal magnon transmission has only been achieved at resonant conditions with gigahertz frequency. It is unclear if nonreciprocity can still be observed for magnons with broad spectrum up to terahertz frequency.

Here we show that by using a magnetic gate, tunable nonreciprocal propagation can be realized in spin Hall effect-excited incoherent magnons, whose frequency covers the spectrum from a few gigahertz up to terahertz. We further identify the direction-dependent magnetic damping as the dominant mechanism for the nonreciprocity, which originates from the interlayer dipolar coupling and works both in the ballistic and diffusive regions of magnons. As a natural result of the chiral magnon-magnon coupling, our findings provide a general mechanism for introducing directional magnon transmission and lead to a design of passively gated magnon transistors for applications of information transmission and processing.

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Research Interests:
Electronic devices, magnetism, spintronics.

Nanopatterned Graphene Based Universal Epitaxy Platform for Single-crystalline Membrane Transfer

H. Kim, S. Lee, S.-H. Bae, K. Lu, K. S. Kim, J. Kim

Sponsorship: DARPA Young Faculty Award (award no. 029584-00001), DOE SETO office (award no. DE-EE0008558), and AFRL (award no. FA9453-18-2-0017)

9.08

Forming freestanding membranes of single-crystalline materials with high material qualities is crucial for diverse emerging applications, including flexible electronics, curved displays, wearable devices, and edge computing. Recently, remote epitaxy is proposed as a method to form freestanding thin films, wherein single-crystalline films are grown on graphene-coated substrates, where the interaction between substrates and epilayers through graphene guide the epitaxial orientation of overlayers. Simultaneously, the presence of graphene weakens the bonding between epilayer and substrate at the interface, which enables exfoliation of epilayers. However, this method can be applied only to the materials with ionicity. Here, we show that graphene with nanopatterns can be universally used to grow single-crystalline materials and peel off the grown film, on virtually any single-crystalline substrates including elemental substrates like silicon and germanium. Graphene can be either grown on the substrate or transferred, followed by patterning to partially expose the substrate. Then, the exposed area enables selective-area epitaxy, and lateral overgrowth enables forming smooth and single-crystalline films on graphene. Since most of the substrate is still covered by graphene, the weak bonding between the graphene and epilayer enables mechanical exfoliation of grown films, enabling the formation of freestanding thin films. Furthermore, the presence of graphene in this approach facilitates growing heteroepitaxial materials with higher crystal quality than conventional heteroepitaxy. Therefore, the proposed method could be universally applied in diverse materials as a new way of realizing freestanding thin films with superior material qualities.

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GaN, III-Vs, optoelectronics, SiGe and Ge.

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Research Interests:
Energy, energy harvesting devices & systems, thermal structures, devices & systems.

Micro-tube Arrays for Enhanced Pool Boiling Heat Transfer

9.09

Y. Song, S. Gong, G. Vaartstra, E. N. Wang

Sponsorship: ARPA-E

Boiling is an essential process in numerous applications including power plants, thermal management of concentrated photovoltaics, water purification, and industrial process steam generation. While previous works have used approaches such as permeable surface structures to enhance critical heat flux (CHF) and micro-cavities to enhance heat transfer coefficient (HTC), the ability to achieve both has been limited. In this work, we investigated micro-tube surface structures, where a cavity is defined at the center of a pillar, as a new structural building block to enhance HTC and CHF values simultaneously in a controllable manner. Surfaces with micro-tube arrays showed more than 60% and 240% enhancements in CHF and HTC values, respectively, compared to those of a smooth surface. We further demonstrated that, by combining micro-pillars and micro-tubes, surfaces can be designed to achieve higher CHF and HTC values than surfaces with only micro-pillar arrays. This work promises guidelines for the systematic surface design for boiling heat transfer enhancement and has important implications for understanding boiling heat transfer mechanisms.

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2D materials, electronic devices, electronics, energy, nanotechnology, organic materials.

Self-Assembled Molecular Junction Bolometers for Mid Infrared Detection

9.10

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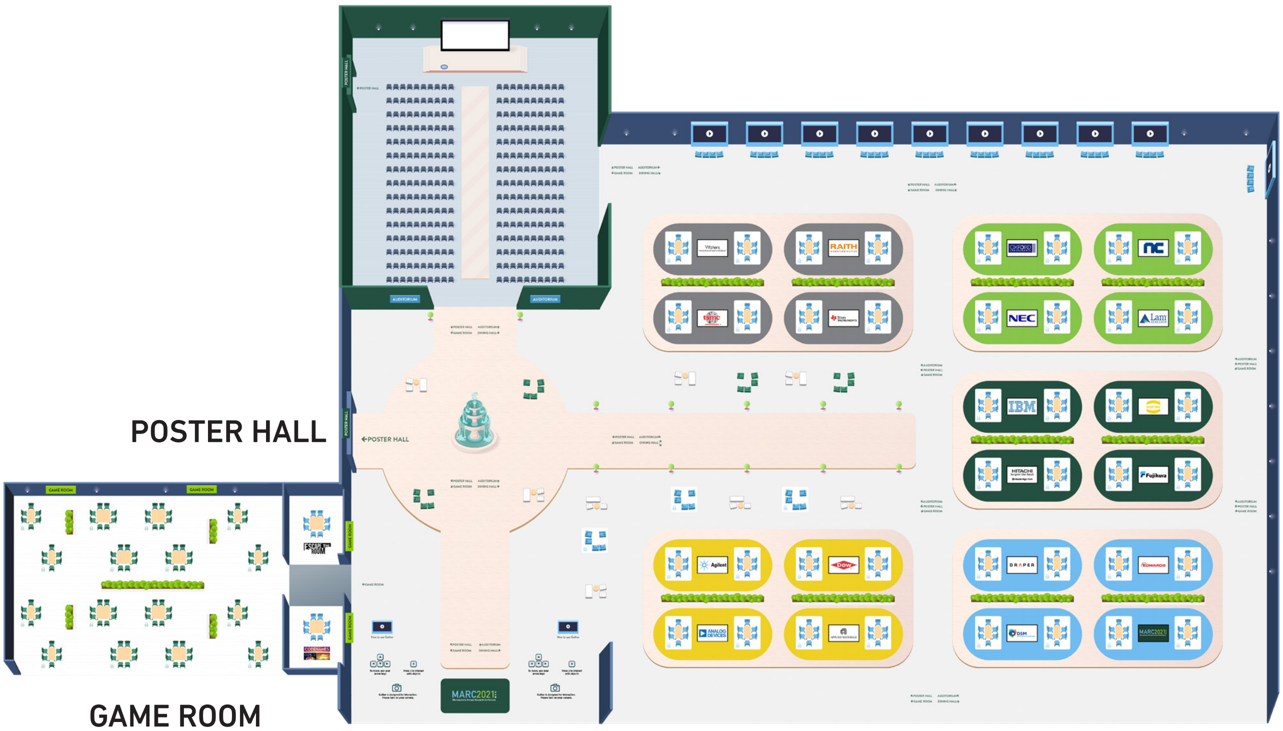
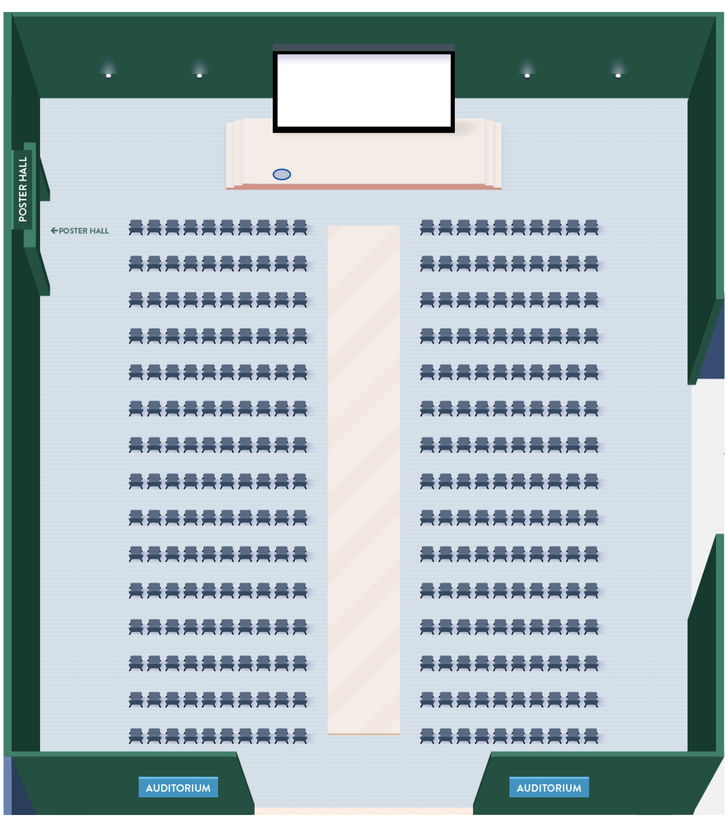
Sponsorship: U.S. ARO through the Institute for Soldier Nanotechnologies, under cooperative agreement number W911NF-18-2-0048, NASA NSTRF program (80NSSC17K0081)

Modern thermal detectors such as vanadium oxide (VOx) bolometers can approach the background limited detectivity of $1.98X10^{10}$ Jones with a flat response over the entire infrared (IR) spectrum. Furthermore, unlike photoconductor/photovoltaic devices, they do not require complex cooling systems to operate in the mid and far infrared, making them suitable for many mid-IR sensing applications. However, many of these devices are slow due to a large thermal time constant, require specialized materials, and/or consume large amounts of power.

A large mechanical sensitivity can be achieved by a mechanically tunable quantum tunneling barrier. The tunneling resistance across the nanometer-sized gap can be changed by several orders of magnitude through a sub-angstrom-scale displacement that can be caused by a change in the device's temperature. Here we demonstrate a suspended metal/self-assembled monolayer (SAM)/metal nanostructure to implement such a mechanically tunable tunneling barrier and use it as an ultra-sensitive bolometric mid-infrared (IR) detector. Fabricated proof-of-concept metal/SAM/metal bolometers yield a temperature coefficient of resistance (TCR) of up to 0.2 K-1, and theoretical predictions show that with further optimization we can achieve TCRs as high as 5 K-1, which is more than one order of magnitude better than the state-of-the-art VOx bolometers. Strain, transport, noise and mid-IR scanning photocurrent microscopy measurement are performed to show the full functionality of the devices. This work demonstrates proof of concept low-power molecular junction bolometers that can be further optimized to compete with either the speed or detectivity of state-of-the-art devices.

GATHER MAP

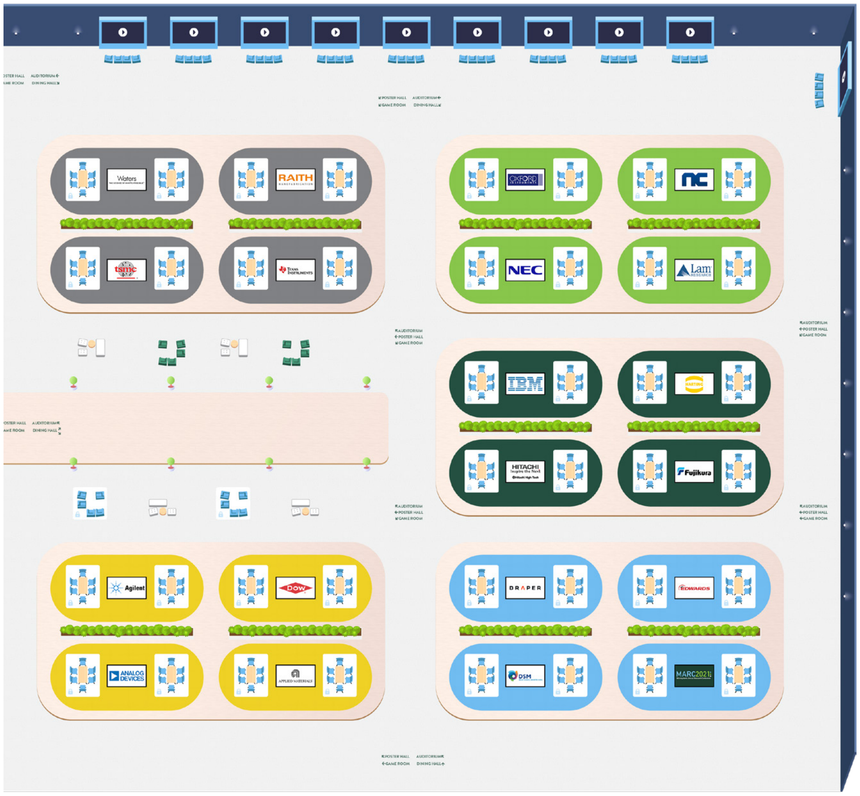




AUDITORIUM

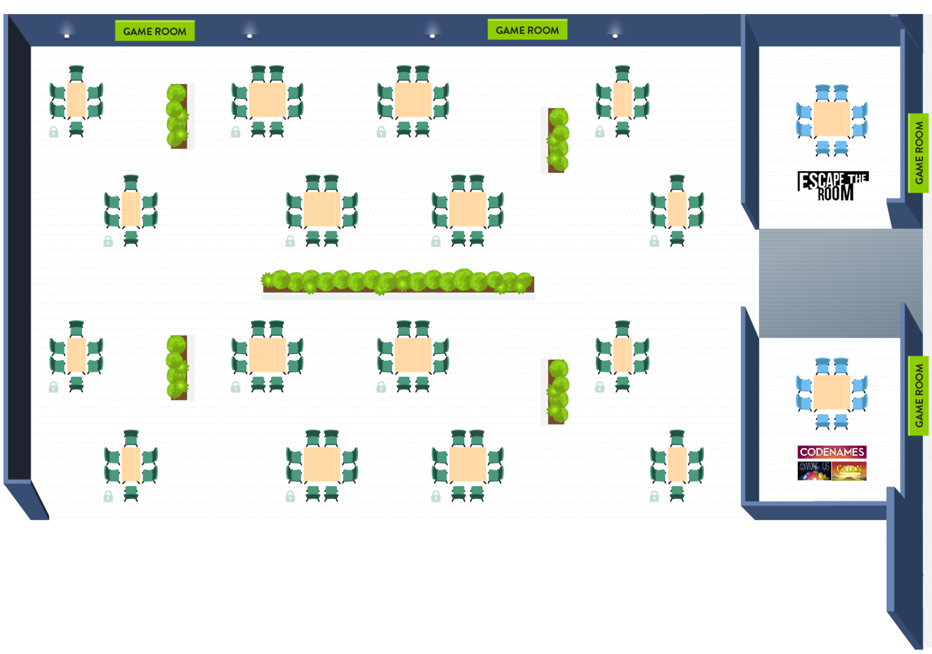
- Opening Remarks
- Keynote
- 60-Second Student Pitches
- Faculty RAP Session
- MARC Comedy Show
- Special Session: COVID-19 Applicable Technologies
- MIG/MAP Pitches
- Closing Ceremony

GATHER MAP



DINING HALL

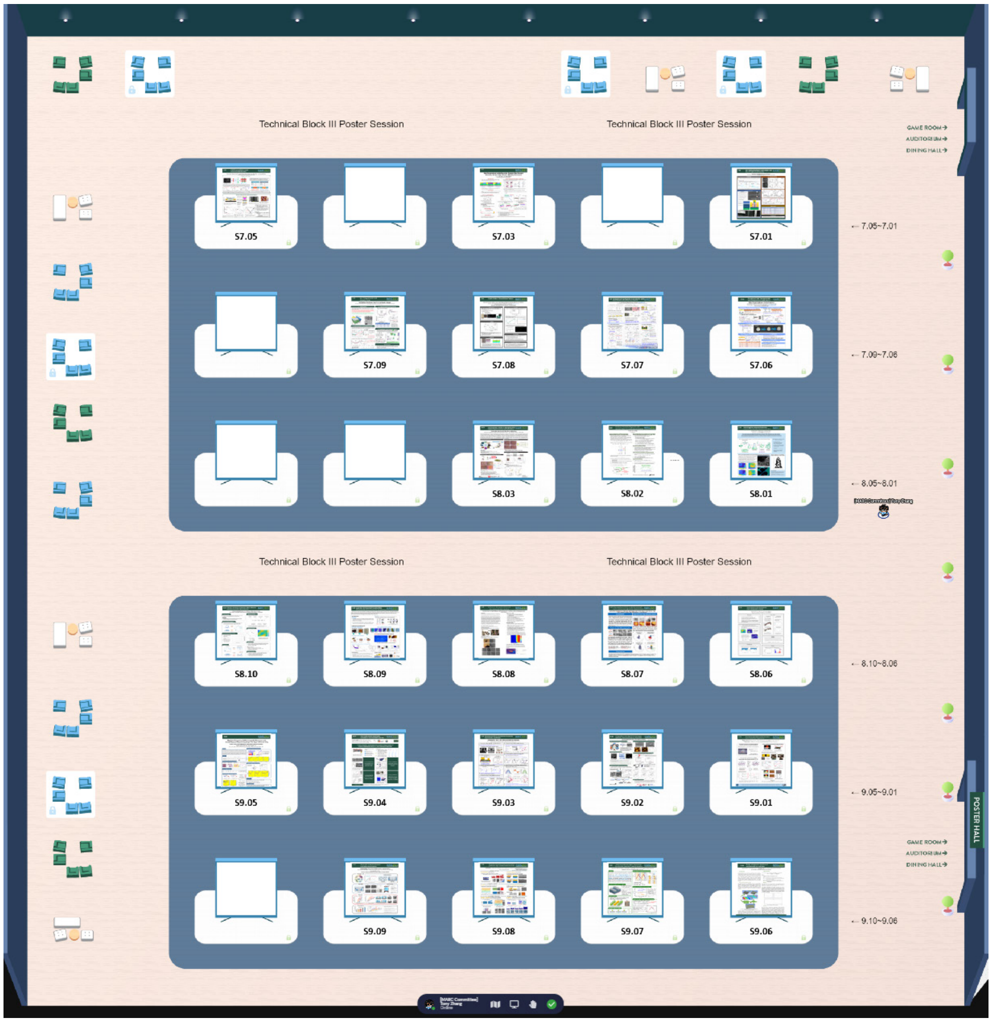
- Dessert Social
- MIG/MAP Networking Lunch



GAME ROOM

- Catan
- Codenames
- Among Us
- Escape The Room

GATHER MAP



POSTER HALL

- Student Poster Sessions

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