MARC2019:

Microsystems Annual Research Conference 2019

MTLEXPO:

Microsystems Technology Laboratories Annual Expo 2019

January 29–30, 2019
Bretton Woods, NH

MICROSYSTEMS TECHNOLOGY LABORATORIES • MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MARC2019:

MICROSYSTEMS ANNUAL RESEARCH CONFERENCE

JANUARY 29–30, 2019 • BRETTON WOODS, NH

Massachusetts Institute of Technology

MTL: MICROSYSTEMS TECHNOLOGY LABORATORIES

MTLEXPO: Microsystems Technology Laboratories Annual Expo 2019

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INTRODUCTION

Dear colleagues,

Welcome to the 2019 Microsystems Annual Research Conference (MARC)! This conference brings together the MIT Microsystems Technology Laboratories (MTL), the Microsystems Industrial Group (MIG), and other MTL associates and friends to celebrate groundbreaking research achievements and make connections for collaborations, careers, and other beneficial relationships. We are delighted that you are able to join us, as we return once again to the beautiful mountains of Bretton Woods, NH, at the Omni Mt. Washington Resort.

MTL and MARC have both evolved over the last three decades, and they continue to evolve. The latest in this evolution is the recently completed MIT.nano building. MIT.nano represents a gigantic opportunity to advance nanoscale research at MIT. MIT.nano will double the clean-room capacity of MTL and will then be able to accommodate new capabilities. In addition, built as the ultimate mechanically- and electromagnetically-quiet space, MIT.nano will provide an environment to advanced analytical equipment to enable the most sensitive measurements, accurate images, and impactful discoveries. MIT.nano stands at the heart of campus, literally and figuratively centered to connect research across departments and disciplines in a truly collaborative push toward a nanoscale future. As this change moves forward, some things remain constant. Through its partnership with MIT.nano, MTL's dedication to impactful nanoscale research, excellent training and teaching, and its close mutually beneficial relationships with industry partners will continue as fresh and relevant as ever.

MARC 2019 features the work of 44 research groups affiliated with 6 departments in the form of 106 technical presentations — a testament to the breadth of research and diversity in MTL. This research spans 10 diverse technical areas across two poster sessions at the conference.

We are excited to announce two exceptional keynote speakers for MARC 2019. Our evening keynote speaker is Dr. Sophie Vandebroek, Vice President of Emerging Technology Partnerships at IBM Corporation. Dr. Vandebroek will provide valuable insights into cooperative connections between academia and industry, becoming a leader in technology and business, and maintaining humanity in the process. Our morning speaker is Dr. Jonathan Rothberg, professor at Yale University, founder of a number of successful genetics startups, and National Medal of Technology and Innovation recipient for the development of next-generation DNA sequencing. Dr. Rothberg's talk will reveal how nanoscale innovations are impacting not just the fields of biology and genetics, but how they are already improving lives through fast, accurate, personalized medicine.

MARC 2019 continues the great tradition of Microsystems Industrial Group (MIG) member pitches started last year. We are thankful to our MIG members for their continued support and participation in MARC.

We are immensely grateful to all presenters for their enthusiastic contributions to the technical content of MARC 2019. We are also thankful for the leadership of MTL Director, Jesús del Alamo, and the support of administrative staff and student volunteers. Finally, we would like to thank the wonderfully collaborative and supportive MTL community. We look forward to a successful and very enjoyable MARC 2019!

Sincerely,
Alex Hanson and Sırma Örgüç
and the MARC2019 Committee

AGENDA

DAY 1: JANUARY 29

7:00 am	**Early Bus Departs MIT**	60 Vassar Street, Cambridge, MA
10:00 am–3:30 pm	**Winter Activities**	Bretton Woods, NH Our attendees can take part in a variety of outdoor winter activities on Mount Washington as well as indoor activities. Activities will only be available for attendees arriving on the early bus (or those coming by private transportation). You are free to check out the indoor pool or sauna, and the truly adventurous may want to try the outdoor pool.
1:00 pm	**Late Bus Departs MIT**	60 Vassar Street, Cambridge, MA
4:00 pm–5:00 pm	**Check-in & Registration**	Hotel Check-in Desk; MARC2018 Registration Desk, Great Hall
5:00 pm–6:00 pm	**Welcome Reception**	Conservatory
6:00 pm–7:15 pm	**Dinner Banquet**	Grand Ballroom
7:30 pm–8:15 pm	**Evening Keynote**	Grand Ballroom Sophie Vandebroek, Vice President of Emerging Technology Partnerships, IBM Corporation
8:15 pm–8:30 pm	**Group Photo**	Grand Ballroom
8:30 pm–10:45 pm	**Evening Activities**	Washington, Jefferson, and Reagan Rooms Pitch practice sessions will take place in the Presidential Ballroom.

AGENDA

Day 2: January 30

7:45 am–8:30 am	**Breakfast** Presidential Foyer
8:30 am–8:45 am	**Opening Remarks** Presidential Ballroom The technical portion of the conference begins with remarks from MTL Director Jesús del Alamo and the MARC2019 co-chairs, Alex Hanson and Sırma Örgüç.
8:45 am–9:30 am	**Technical Keynote** Presidential Ballroom Jonathan Rothberg, Scientist and Entrepreneur
9:30 am–10:00 am	**MIG/FFA Pitches** Presidential Ballroom
10:00 am–11:00 am	**60-Second Poster Pitch** Presidential Ballroom Session 1 - Devices: Emerging Technologies Session 3 - Circuits: Analog, RF, Power Session 5 - Photonics/Optoelectronics 1 Session 7 - Nanotechnology & Nanomaterials Session 9 - Solar, Energy, & Environment
11:15 am–12:30 pm	**Poster Session** Grand Ballroom Sessions 1, 3, 5, 7, and 9.
12:30 pm–1:30pm	**MIG Networking Lunch** Dining Room/Sun Dining Room
1:30 pm–2:30 pm	**60-Second Poster Pitch** Presidential Ballroom Session 2 - Devices: Logic, Power, & Vacuum Session 4 - Circuits: Energy-efficient AI Session 6 - Photonics/Optoelectronics 2 Session 8 - Materials & Manufacturing Session 10 - Medical Devices and Biotechnology
2:30 pm–3:45 pm	**Poster Session** Grand Ballroom Sessions 2, 4, 6, 8, and 10.
4:00 pm–4:30 pm	**Closing Ceremony** Presidential Ballroom Award presentations and a final note from our organizers.
4:30 pm–4:45 pm	**Buses Depart for MIT** Hotel Main Entrance

DAY 1: EVENING KEYNOTE

DR. SOPHIE V. VANDEBROEK is the Vice President of Emerging Technology Partnerships at IBM Corporation, leading strategic initiatives to scale IBM's ecosystems. One great example of such partnership is the MIT-IBM Watson AI Lab which just celebrated its first anniversary. Sophie was previously the Chief Operating Officer for IBM Research, one of the world's most influential corporate research labs with 5,000 researchers in over 20 locations across the globe. IBM is pioneering promising and disruptive technologies that will transform industries and society, including AI, blockchain and quantum computing.

Prior to joining IBM, Sophie was with Xerox Corporation for over 25 years, including a decade as their Chief Technology Officer. She was responsible for leading Xerox's global research labs including PARC Inc. which provides custom R&D services to enterprises, startups and government agencies.

Sophie is a Fellow of the Institute of Electrical & Electronics Engineers (IEEE) and holds 14 US patents. She also serves on the Board of Directors of IDEXX Corporation and on the advisory council of the Dean of the Engineering at MIT. Sophie earned a master's degree in engineering from KU Leuven, Belgium, and a PhD in electrical engineering from Cornell University, Ithaca, NY.

SOPHIE VANDEBROEK
Vice President of Emerging Technology Partnerships
IBM Corporation

DAY 2: MORNING KEYNOTE

JONATHAN M. ROTHBERG

Scientist and Entrepreneur

DR. JONATHAN ROTHBERG is a scientist and entrepreneur who was awarded the National Medal of Technology and Innovation, the nation's highest honor for technological achievement, by President Obama for inventing and commercializing high-speed DNA sequencing. He is the founder of multiple life science and medical device companies including CuraGen, 454 Life Sciences, Ion Torrent, RainDance Technologies, Hyperfine Research, Quantum-Si, Lam Therapeutics, and Butterfly Network.

The idea for massively parallel ("Next-gen") DNA sequencing came to Rothberg when his infant son was rushed into intensive care, helping him realize the critical importance of genomics to human health. With 454 Life Sciences, Rothberg brought to market the first new way to sequence genomes since Sanger and Gilbert won the Nobel Prize for their method in 1980. The New England Journal described Rothberg's innovation as "The New Age of Molecular Diagnostics", and Science magazine called it one of the top 10 breakthroughs of 2008. With 454's technology, Rothberg sequenced the first individual human genome (James Watson's Genome, Nature cover), and with Svante Paabo he initiated the first large-scale effort to sequence ancient DNA (The Neanderthal Genome Project). Under his leadership, 454 undertook the first deep sequencing of a cancer, helped understand the mystery behind the disappearance of the honey bee, uncovered a new virus killing transplant patients, and elucidated the extent of human genomic variation—work recognized by Science magazine as the breakthrough of the year in 2007. Rothberg went on to invent semiconductor chip-based sequencing, with which he sequenced the genome of Gordon Moore (Moore's Law, Nature cover), paving the way for the $1,000 Genome. His contributions to the field of sequencing include the first non-bacterial cloning method (cloning by limited dilution) and the first massively parallel DNA sequencing method (parallel sequencing by synthesis on a single substrate), concepts that have formed the basis for all subsequent next generation sequencing technologies.

Most recently, with Butterfly Network, Rothberg developed the first ultrasound instrument built entirely on a semiconductor chip, giving it greater imaging flexibility than any device on the market. Butterfly's device received the widest FDA clearance ever given to an ultrasound probe, making it the world's first handheld whole-body scanner at a cost 50-fold less than existing devices, launching an era of democratized medical imaging.

Rothberg was born in 1963 in New Haven, Connecticut. He earned a B.S. in chemical engineering from Carnegie Mellon and an M.S., M.Phil, and Ph.D. in biology from Yale. He is the first person to be named a World Economic Forum's Technology Pioneer four separate times, is an Ernst and Young Entrepreneur of the Year, is the recipient of The Wall Street Journal's First Gold Medal for Innovation, Nature Methods First Method of the Year Award, The Irvington Institute's Corporate Leadership Award in Science, the Connecticut Medal of Technology, the DGKL Biochemical Analysis Prize, and an Honorary Doctorate of Science from Mount Sinai. Rothberg is a member of the National Academy of Engineering, the Connecticut Academy of Science and Engineering, is a trustee of Carnegie Mellon, and an Adjunct Professor of Genetics at the Yale.

MIG MEMBER COMPANIES

Analog Devices, Inc.
Applied Materials
Draper
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Foxconn Electronics
HARTING
Hitachi High-Technologies
IBM
Lam Research Co.
NEC
TSMC
Texas Instruments

The Microsystems Industrial Group (MIG) is an association of corporate members of MIT's Microsystems Technology Laboratories. Founded during the early eighties, the MIG played a prominent role in the creation of MTL, and in providing critical insight into the programmatic directions of MTL. Continuing this year at MARC2018, MIG members are invited to give two-minute pitches about activities at their respective companies.

POSTER SESSIONS

SESSION 1: DEVICES: EMERGING TECHNOLOGIES

SESSION 2: DEVICES: LOGIC, POWER, & VACUUM

SESSION 3: CIRCUITS: ANALOG, RF, POWER

SESSION 4: CIRCUITS: ENERGY-EFFICIENT AI

SESSION 5: PHOTONICS/OPTOELECTRONICS 1

SESSION 6: PHOTONICS/OPTOELECTRONICS 2

SESSION 7: NANOTECHNOLOGY & NANOMATERIALS

SESSION 8: MATERIALS & MANUFACTURING

SESSION 9: SOLAR, ENERGY, & ENVIRONMENT

SESSION 10: MEDICAL DEVICES AND BIOTECHNOLOGY

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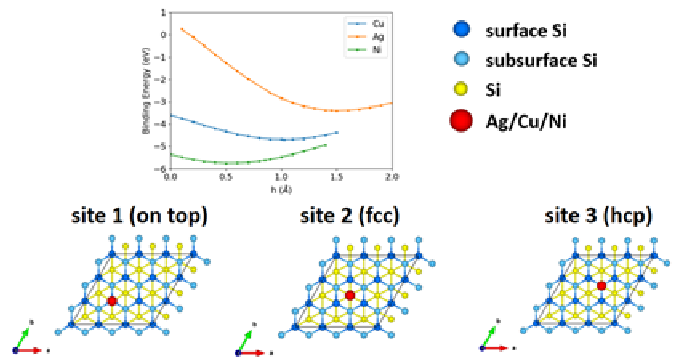
Dewetting Principles of Metallic Filament in Silicon-based Resistive Random Access Memory

1.01

C. Choi, S. Tan, P. Lin, H. Yeun, J. Kim

Sponsorship: Microsystems Technology Laboratories/ Research Laboratory of Electronics

Silicon-based resistive random access memory using diverse active metals has been investigated in terms of the formation of metallic filament. The preferential locations of metals in bulk silicon (111) were found to be face-centered cubic structure (fcc). To elucidate dewetting behaviors of metals along with dislocation in epitaxial film, binding energy and diffusion barrier of metals (Ag, Cu, Ni) in bulk silicon (111) and silicon surface were calculated using norm-conserving pseudo-potentials and the generalized gradient approximation (GGA) to the exchange-correlation energy. This work will help to understand formation, expansion, and shrinkage of filament based on the properties of active metals in conductive bridging random access memory.



▲ Three different configuration of metals in silicon (111) and binding energy of each metal (Ag, Cu, Ni)

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Research Interests:
Electronic devices, electronics, energy, energy harvesting devices & systems, nanomaterials, nanotechnology, photovoltaics.

Control of Conductive Filaments in Resistive Switching Oxides

1.02

K. J. May, Y. R. Zhou, T. Ando, V. Narayanan, H. L. Tuller, B. Yildiz

Sponsorship: IBM Corporation

There has been a growing interest in using specialized neuromorphic hardware for artificial neural network applications such as image and speech processing. These neuromorphic devices show promise for meeting the significant computational demands of such applications with higher speed and lower power consumption than software-based implementations. One approach to achieving this goal is through oxide thin film resistive switching devices arranged in a crossbar array configuration. Resistive switching can mimic several aspects of neural networks, such as short- and long-term plasticity, via the dynamics of switching between multiple analog conductance states—dominated by the creation, annihilation and movement of defects within the film (such as oxygen vacancies). These processes can be stochastic in nature and contribute significantly to device variability, both within and between individual devices.

This study focuses on reducing the variability of the set/reset voltages and enhancing control of the conductance state with voltage pulsing using model systems of HfO_2 and $SrTiO_3$ grown on Nb:$SrTiO_3$ and Si/TiN substrates, by control of film synthesis parameters and composition. By comparing the electrical characteristics of a large number of devices (~100) from each processing condition, film growth conditions may be optimized for maximum resistive switching repeatability. Because the device requirements for practical resistive switching arrays are significant, controlling the variability of individual devices will likely be a consideration for every fabrication and processing step. This work provides a significant step towards understanding the mechanisms behind device variability and achieving devices that meet the strict requirements of neuromorphic computing.

Design and Characterization of Superconducting Inductive Processors for Acceleration of Deep Neural Network Training

1.03

M. Onen, B. A. Butters, E. A. Toomey, K. K. Berggren

Training of deep neural networks (DNNs) is considered as a highly computation intensive task. A variety of accelerator approaches have been proposed to reduce time and power cost of these operations. Recent studies have shown that mixed-signal designs involving crossbar architectures are capable of achieving acceleration factors as high as 30,000x. However, no technology has been developed to date that can realize the strict device requirements. This paper presents the superconducting nanowire-based inductive processing element (SNIPE) as an inherently suitable cross-point device. The SNIPE has many programmable non-volatile states that can be used in analog multiplication. Operation of these devices in a crossbar is described and supported with electro-thermal simulations. Validation of the concept in an actual DNN training is shown using an emulator that uses characterized device response as a reference. Ultimately, devices presented in this work show excellent characteristics and have the potential to revolutionize neural network training.

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Research Interests:
2-D materials, electronic devices, electronics, field-emitter devices, GaN, III-Vs, integrated circuits, nanomanufacturing, nanomaterials, nanotechnology, Si, SiGe and Ge.

Three-dimensional Vertical epiRAM Array for Neuromorphic Computing

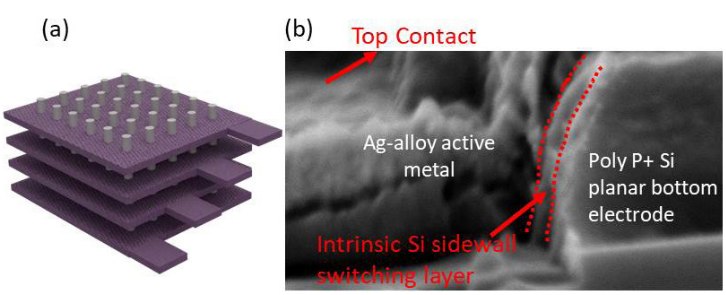
1.04

Y. Park, S. H. Tan, P. Lin, H. Yeun, C. Choi, J. Kim

Sponsorship: Samsung

Rapidly improving artificial intelligence systems suffer from enormous computing power and traffic to handle huge data in classical computing architecture. In this situation, non-volatile resistive switching device, or resistive RAM (RRAM), shows great promise because the RRAM crossbar array can carry out the weighted sum operation, efficient/parallel in-memory computing paradigms. 3D integrated RRAM array can have much more advantage over conventional 2D crossbar arrays with pronounced high integration density, smaller wire resistance and higher input/output bandwidth.

We developed the epitaxial resistive switching device(epiRAM) that possesses desired characteristics, such as good retention/endurance, switching uniformity, high analog on/off ratio and linear conductance update. Using HSPICE, we studied the performance of 3D RRAM computing array to optimize operation parameters with a standard device we fabricated. Based on simulation, we can demonstrate epiRAM 3D structure to carry out image storage and small-size DNN with our current device performance, such as device variations and linear conductance update.



▲ Figure (a) shows an example of 3D RRAM structure. Figure (b) is SEM image of unit device and explains each component.

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Research Interests:
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Probing Local Environments of Implanted Defect Centers

1.05

E. Bersin, M. Walsh, S. van Dam, S. Mouradian, M. Degen, D. R. Englund, R. Hanson

Sponsorship: National Aeronautics and Space Administration, U.S. Department of Defense, National Science Foundation, Siebel Foundation

Defect centers in solids play a wide range of roles in advancing technology, from acting as dopants in electronics to acting as memories for quantum computing. Ion implantation is a typical means of introducing such defects when spatial localization is required, as is often the case for technologies requiring isolation of single defect centers such as single photon sources. However, the act of implantation induces significant lattice damage, creating vacancies and other potentially undesirable defects. While typical implantation recipes use high-temperature annealing to remove some of these defects, the extent to which this process can heal lattice damage is not well studied. Here, we probe the local environment of nitrogen-vacancy centers formed from both implanted and unimplanted nitrogen atoms, using the optical linewidth as a proxy for stability of the local charge environment. We find that the implanted systems exhibit markedly degraded optical lines compared to their native counterparts. This indicates that applications requiring single defects with otherwise clean local environments, such as quantum sensing or quantum computing, may be hindered by relying on implantation for defect creation.

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Research Interests:
Quantum devices, quantum computation and information.

Extending Quantum State Tomography for Superconducting Quantum Processors

1.06

F. Vasconcelos, M. Kjaergaard, T. Orlando, S. Gustavsson, W. Oliver

Sponsorship: Draper Laboratory SuperUROP Fellowship

Quantum State Tomography (QST), or the reconstruction of the density matrix of a quantum state via measurements, is critical to ensure the proper functionality of qubits and quantum operations in a quantum computer. Currently, there exist tomography implementations for 1- and 2-qubit systems in our superconducting quantum processor. In this work, we develop quantum state tomography for 3-qubit systems and expand to n-qubit systems. For 3-qubit state tomography, we generalize the current 1- and 2-qubit process, which includes training a Support Vector Machine to discern states and learn Beta parameters, followed by Maximum Likelihood Estimation (MLE) to construct the density matrix. This QST code will be tested and verified on actual experimental data from a 3-qubit system, with 2-qubit entanglement. We will then extend this QST implementation to n-qubits, which poses an interesting algorithms challenge, since the size of the density matrix scales exponentially with the number of qubits. Since recent quantum information research suggests MLE is inadmissible for QST, work will also be done to improve the QST algorithm itself, by trying and comparing different machine learning and statistical approaches. Ultimately, this will be implemented as a code-suite, integrated in the analysis software toolbox for the quantum processor, and verified on real data from state-of-the-art qubit experiments. Additional work is being done to speed up the baseline measurement process of our system. Currently, each of the hundreds to thousands of qubit measurements being performed prior to QST are individually sent to the classical control computer for processing. This, however, is a slow, inefficient, and redundant process, since generally only the relative number of measurements in the ground and excited state is required for QST. We use an FPGA to directly map the qubit readings onto the I-Q (complex voltage phase plane) and classify them before being sent to the control computer.

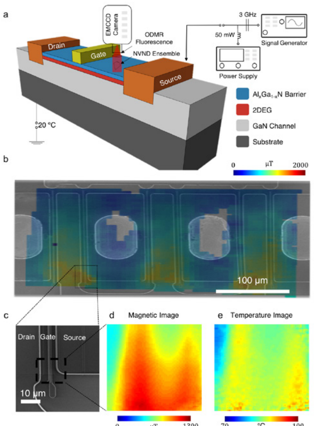
Widefield Thermomagnetic Imaging of Power Electronics using Nanoscale Quantum Sensors

1.07

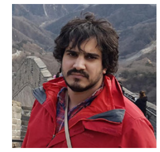
C. Foy, L. Zhang, M. Trusheim, K. Bagnall, E. N. Wang, D. R. Englund

Sponsorship: Master Dynamic Limited

Thermal and magnetic imaging are of particular interest for many applications. However, a simultaneous wide-field thermomagnetic measurement has not been developed. We demonstrate the principle and application of a promising technique which offers (i) wide-field imaging of dynamic phenomenon, (ii) high sensitivity,(iii) simultaneous measuring of temperature and magnetic field under ambient conditions, and (iv) compatibility with standard microscopes. Our technique uses the nitrogen-vacancy (NV) center hosted within diamond nanocrystals (NVNDs) which has emerged as a leading solid-state quantum sensor. We apply this technique to study the open problem of gallium nitride high electron mobility transistor (GaN HEMT) failure. We image the magnetic field profile of the HEMT and observe the current falloff from the channel stop. This technique should provide significant contributions to a variety of frontier research areas from material science to device-level characterization.



◄ NVND microscopy of a Gan HEMT. a.) Schematic of the experimental setup. b.) Magnetic field image of a multi-fingered Gan HEMT when in operation, overlayed onto an SEM. c.) SEM of channel stop. d-e.)Magnetic field and temperature image of the channel stop.



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Research Interests:
2D materials, biological devices & systems, electronic devices, electronics, GaN, integrated circuits, MEMS & NEMS, nanotechnology, quantum devices.

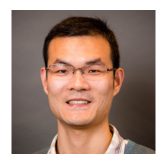
Perpendicular Standing Spin Waves Generation in Magnetic Metal-insulator Hybrid Structures

1.08

Y. Fan, L. Liu

Magnons (or spin waves) are collective excitations of electrons' spin angular momenta in magnetic or non-magnetic materials. Magnons can be used to transport spin current and enable information transmission with much higher energy efficiency than conducting electron spin current. The excitation and tunability of magnons in low-damping magnetic insulators, e.g., the yttrium iron garnet (YIG), is particularly interesting because it could offer much longer magnon propagation length and potential broad microwave applications.

Here, we study a platinum/YIG/permalloy hybrid structure, where YIG is the magnetic insulator and permalloy (Py) is a low-damping ferromagnetic metal. This hybrid structure was grown on the gadolinium gallium garnet (GGG) substrate by magnetron sputtering. Through external microwave excitation, the YIG layer and the Py layer can be excited to reach the ferromagnetic resonance modes individually. We have detected the spin current signal from the Py spin pumping process transmitted through the YIG layer and converted to voltage signal in the platinum (Pt) layer by the inverse spin Hall effect. More importantly, we have detected additional resonance peaks and spin pumping voltage signals which correspond to the perpendicular standing spin waves (PSSW) in the YIG layer. At specific frequency, this PSSW in YIG can be coupled with the magnon mode in Py and facilitate the magnon spin transport from the Py layer to the bottom Pt layer. This result indicates that the PSSW in YIG layer could potentially tune the magnon chemical potential of YIG, therefore enhancing the magnon spin transport conductivity from the Py layer to the Pt layer. Our results suggest that the magnon spin transport can be tuned by the ferromagnetic resonance, allowing effective coherent control of magnonic devices.



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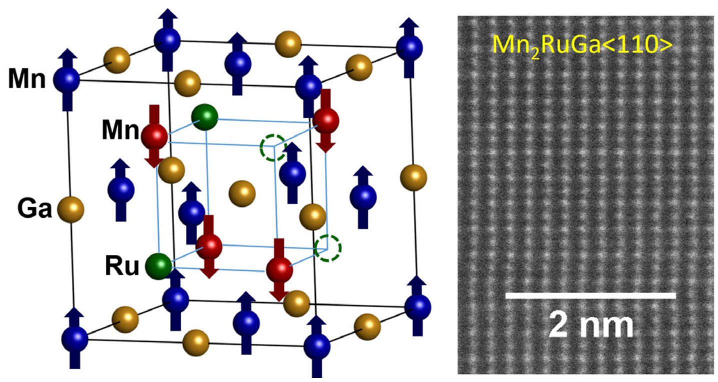
Spin-orbit Torque Switching in a Nearly Compensated Heusler Ferrimagnet

1.09

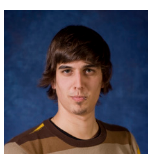
J. Finley, C.-H. Lee, P. Huang, L. Liu

Sponsorship: TSMC

Traditional spintronics devices employ ferromagnetic materials to store information, however, there has been recent interest in using antiferromagnetic materials for information storage because they promise to be more stable and secure, with higher switching speeds. Ferrimagnetic materials combine the advantages of the low magnetic moment in an antiferromagnet and the easy magnetic reading of a ferromagnet. It was recently demonstrated that compensated ferrimagnetic half metals can be realized in Heusler alloys, where high spin polarization, zero magnetic moment, and low magnetic damping can be achieved at the same time. In this work, by studying the spin-orbit torque induced switching in the Heusler alloy $Mn_2Ru_{1-x}Ga$, we found that efficient current-induced magnetic switching can be achieved in a nearly compensated sample with strong perpendicular anisotropy and large film thickness. Our work demonstrates the possibility of employing compensated Heusler alloys for fast, energy-efficient spintronic devices.



◄ Crystal structure of Heusler alloy $Mn_2Ru_{0.5}Ga$ and high-resolution scanning transmission electron microscope (STEM) image from a 100 nm Mn_2Ru_1Ga sample.



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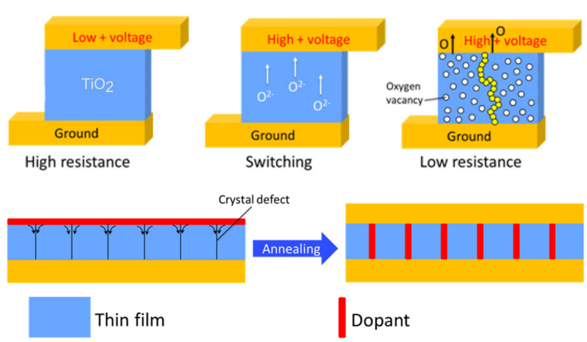
Control of the Density, Location and Properties of Conducting Filaments in TiO_2 by Chemical Disorder for Energy-efficient Neuromorphic Computing

1.10

N. Emond, B. Yildiz

Sponsorship: Fonds de Recherche du Québec—Nature et Technologies (FRQNT)

Inspired by the efficiency of the brain, redox-based resistive switching (RS) random access memories are considered as the next generation devices to mimic neuromorphic core architectures for pattern recognition and machine learning due to their predicted high memory density, energy-efficiency and speed. Within their metal–insulator–metal architecture, these devices store binary code information using the electric field-induced resistance change of the insulating layer by conductive filament (CF) formation and rupture. However, a lack of control on the location and spacing of CFs formation, which occur at chemical and structural defects, and or their properties cause detrimental variation in the device. We recently initiated a study on the effect of strain on the microstructure, chemistry and RS properties of TiO_2 thin-films to get insights into defect formation in view of selectively doping along these defects to eliminate stochasticity in CF formation.



◄ Resistive switching mechanism in a TiO_2 thin film by formation of conductive filaments and its control by selective doping at microstructural defects

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Digital-etch Effect on Transport Properties of III-V Fins

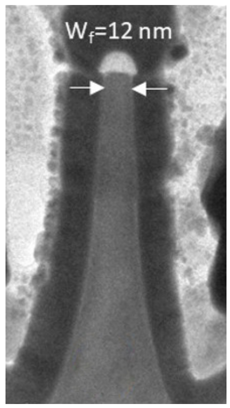
2.01

A. Vardi, L. Kong, X. Zhao, J. A. del Alamo

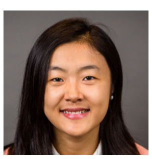
Sponsorship: DTRA, E3S, Lam Research Corporation

One of the key process technologies to improve the interface quality of modern transistors, such as FinFETs, is digital etch (DE). This is a self-limiting etching process that consists of dry oxidation of the semiconductor surface and wet etch of the oxide. Digital etch is also the last process step before the gate oxide is deposited over the fins in FinFETs. It, therefore, plays a crucial role in surface preparation and holds the key for further improvements to device transport and electrostatics.

In this work, we compare the electrical performance of two sets of InGaAs FinFETs processed side-by-side that differ only in the type of digital etch that is applied. In one case, the oxide removal step was accomplished using H_2SO_4, in the other, HCl was used. From the analysis of the electrical data, we conclude that HCl yields a higher mobility but lower carrier concentration at comparable overdrive. However, for highly scaled fins, H_2SO_4 sample performs better.



◄ TEM image of FinFET device with fin width of 12 nm.



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Research Interests:
Displays, electronic devices, III-Vs, lasers, MEMS & NEMS, nanotechnology, optoelectronics, photonics, quantum devices, sensors

Impact of Fin Width on Transport in InGaAs FinFETs

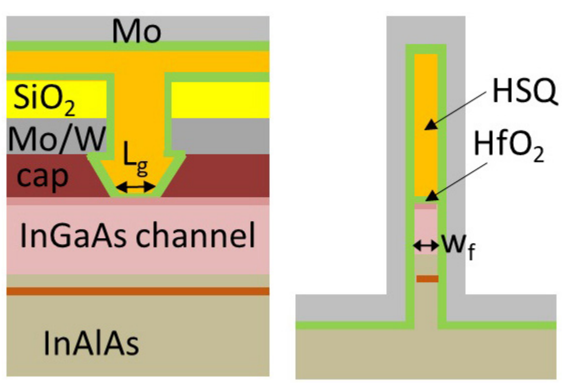
2.02

X. Cai, A. Vardi, J. Grajal, J. A. del Alamo

Sponsorship: DTRA

InGaAs is a promising n-channel material candidate for future sub-7nm CMOS technology node. InGaAs FinFETs have drawn much interest, as they provide both superb transport advantages and great scaling potential. Recently, impressive InGaAs FinFETs with 5 nm fin width and record aspect ratio have been demonstrated. However, transconductance rapidly degrades when fin width is scaled down to nanometer-range dimensions. Our study focuses on understanding this important problem.

Part of the issue is that III-V semiconductors lack a good native oxide. Severe oxide trapping in deposited oxides has been reported, resulting in hysteresis, threshold voltage instability and frequency dispersion in InGaAs MOSFETs. In this work, we use high-frequency measurement techniques to isolate the intrinsic characteristics in InGaAs FinFETs free from the influence of oxide trapping. We find that oxide trapping leads to a severe underestimation of the transport characteristics of thin InGaAs fins.



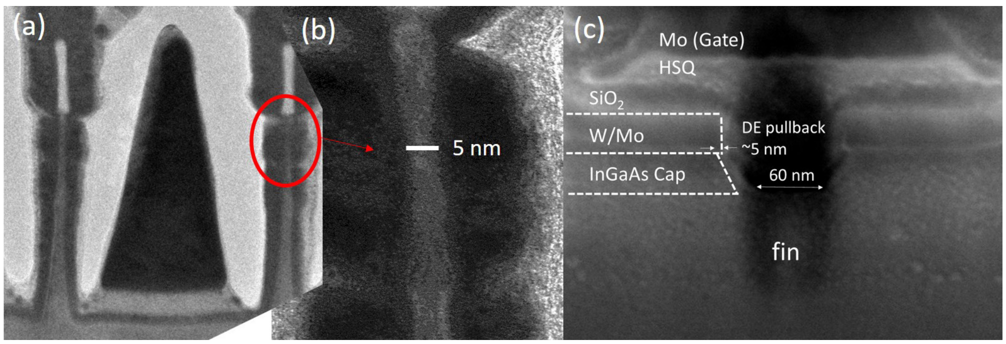
◄ Cross-sectional schematic of InGaAs FinFET along the channel and fin directions.

Excess Off-state Current in InGaAs FinFETs

2.03

X. Zhao, A. Vardi, J. A. del Alamo
Sponsorship: NSF, SRC, Lam Research

We present a detailed study of the high leakage current in scaled self-aligned InGaAs FinFETs, a pressing concern undermining its potential for low-power electronics. In long-channel devices, band-to-band tunneling at the drain-end of the channel is shown to be the root cause of excessive leakage. This conclusion emerges from its characteristic electric field and temperature behavior and the absence of gate length and fin width dependencies. In short-channel devices, off-state current is significantly larger and it increases as the gate length shortens or the fin widens. We attribute this to current multiplication through the gain of a floating-base parasitic bipolar transistor inside the MOSFET. The bipolar current gain in short-channel devices rises as the gate length shortens and decreases as the fin width narrows. In long channel devices, the current gain drops exponentially due to base recombination, enabling the extraction of electron diffusion length in the transistor body.



▲ (a and b) TEM images of finished device with W_f = 5 nm across the channel (c) FIB images along the fin of finished devices with L_g = 30 nm

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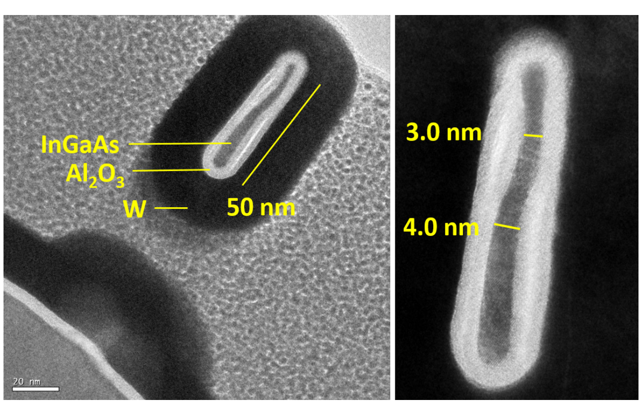
Thermal Atomic Layer Etching and Sub-5 nm InGaAs FinFETs

2.04

W. Lu, Y. Lee, J. Murdzek, J. Gertsch, A. Vardi, L. Kong, S. M. George, J. A. del Alamo
Sponsorship: DTRA, SRC, Lam Research, Intel, and NSF

As CMOS technology continues to scale down to 3-D device structures, semiconductor manufacturing becomes more and more challenging. In recent years, 3D transistors with sub-10 nm physical sizes have been demonstrated. To push forward, breakthrough in device fabrication technologies is required with Ångstrom-scale precision and fidelity.

In this research, we demonstrated the first III-V 3D transistors with sub-5 nm fin width. This is made possible by the development of a novel technology called Thermal Atomic Layer Etching (ALE). Thermal ALE is a reverse process of the Atomic Layer Deposition (ALD). It is plasma-free, chemistry-based, and it can be applied with ALD in an in-situ approach. We have achieved a highly controllable etching rate of InGaAs of merely 0.2 Å/cycle. Moreover, we illustrated the device worthiness of the ALE technique by fabricating the most aggressively scaled InGaAs FinFETs to date, with record fin width down to 2.5 nm. Record device characteristics highlight the extraordinary device potential of the in-situ ALE-ALD process.



◄ Cross-section TEM images of InGaAs suspended fin with minimum fin width of 3 nm.

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Electronic devices, integrated circuits, nanomaterials, nanotechnology.

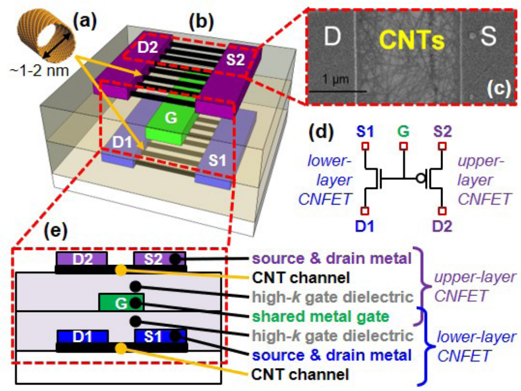
DISC-FETs: Dual Independent Stacked Channel Field-effect Transistors

2.05

P. S. Kanhaiya, G. Hills, D. A. Antoniadis, M. M. Shulaker

Sponsorship: Analog Devices, Inc., National Science Foundation, DARPA

We experimentally demonstrate a three-dimensional (3-D) field-effect transistor (FET) architecture leveraging emerging nanomaterials: Dual Independent Stacked Channel FET (DISC-FET). DISC-FET is comprised of two FET channels vertically integrated on separate circuit layers separated by a shared gate. This gate modulates the conductance of both FET channels simultaneously. This 3-D FET architecture enables new opportunities for area-efficient 3-D circuit layouts. The key to enabling DISC-FET is low-temperature processing to avoid damaging lower-layer circuits. As a case study, we use carbon nanotube (CNT) FETs (CNFETs) since they can be fabricated at low temperature (e.g., <250°C). We demonstrate wafer-scale CMOS CNFET-based digital logic circuits: 2-input "not-or" (NOR2) logic gates designed using DISC-FETs with independent NMOS CNT channels below and PMOS CNT channels above a shared gate. This work highlights the potential of 3-D integration not only for enabling new 3-D system architectures, but also new 3-D FET architectures and 3-D circuit layouts.



◄ CNFET-based DISC-FET. (a) Carbon nanotube (CNT). (b) DISC-FET 3-D illustration (c) Scanning electron microscope (SEM) image of the upper-layer CNFET. (d) 5-terminal circuit schematic of DISC-FET, including 1 PMOS FET and 1 NMOS FET (e) Cross-section showing vertically integrated layers.

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Gate Dielectric Reliability under Tensile Mechanical Stress for GaN Field-effect Transistors

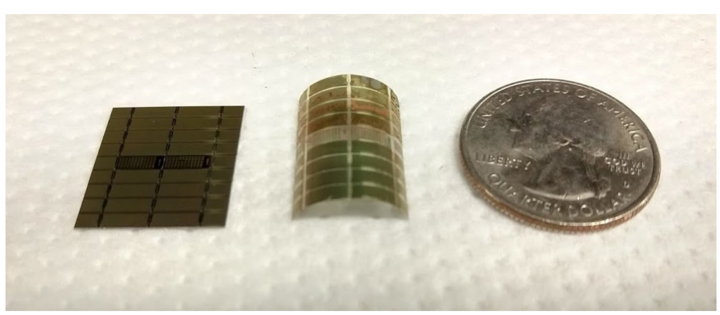
2.06

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

Sponsorship: Texas Instruments

Energy-efficient electronics are gaining attention to answer the growing demand for energy. GaN Metal Insulator Semiconductor High Electron Mobility Transistors (MIS-HEMTs) show great promise as high-voltage power transistors. GaN MIS-HEMTs are suited to replace conventional silicon-based devices as silicon reaches theoretical limits. However, key reliability issues including time-dependent dielectric breakdown (TDDB) limit widespread commercial adoption.

The large current drive of GaN MIS-HEMTs stems from the 2-dimensional electron gas (2DEG) at the AlGaN/GaN interface that results from piezoelectric polarization. To improve and tune performance, device engineers design the gate stack to induce desired changes to mechanical strain and therefore 2DEG density. However, the impact of mechanical strain on TDDB of GaN MIS-HEMTs is unclear. In this work, we report the changes, or lack thereof, in TDDB with tensile mechanical stress on industrially prototyped GaN MIS-HEMTs.



◄ 254 µm thick GaN on Si chip. Middle) Dry etched (40 µm thick) GaN on Si chip with natural bending along the channel direction.

Gallium Nitride FinFETs for High Linearity Applications

2.07

Q. Xie, G. J. Schlenvogt, T. Jokinen, T. Palacios

Sponsorship: DARPA

Enhancing the linearity of gallium nitride (GaN) high electron mobility transistors (HEMTs) is essential in RF applications in order to reduce intermodulation distortion and gain compression. Fin nano-structure emerges as a promising candidate to modify the shape of the transconductance (gm) vs. gate voltage (VG) curve so as to improve the device linearity.

With the aid of simulation studies, we aim to understand the operation of fin-shaped devices in greater detail, including the origins of the device performance. A physics-based analytical model will be developed. Lastly, using the MIT Virtual Source compact model, the linearity of the developed devices for RF power amplifiers will be evaluated. These fin structures open up additional design space in the width dimension, hence allowing for greater possibility to engineer the device design to achieve the desired characteristics.

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Breakdown Mechanism in Vertical GaN Power Fin-FETs

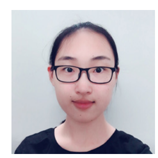
2.08

Names: X. Zou, T. Palacios

Sponsorship: MIT SuperUROP

Compared to conventional silicon, gallium nitride (GaN) is much more capable of operating under high temperatures and high voltages due to its superior material properties. In the past 20 years, transistors fabricated with GaN have been extensively studied, and lateral GaN transistors on Si substrates with operating voltage up to 650 V have already been commercially available. However, for high-power applications that require voltage beyond 650 V, such as in the field of electric vehicles, the vertical GaN power transistors are preferred. A normally-off vertical GaN power Fin-FET with a breakdown voltage of 1200 V was demonstrated last year. While other devices still require p-GaN layers, the vertical GaN power Fin-FET only requires n-GaN layers, and it has successfully avoided the risk and material uncertainty that used to originate from the p-GaN layers.

Although a high breakdown voltage has been demonstrated in previous works, it is believed that their breakdown voltage can be increased further. Understanding the breakdown mechanism is the key to predict the device performance, and it can also give researchers more information to improve its breakdown voltage. However, there hasn't been any systematic study done on the breakdown voltage mechanism of vertical GaN power Fin-FETs. For instance, while conventional MOSFETs experience avalanche breakdown, no avalanche capability has been reported in vertical GaN power Fin-FETs so far. This has inspired the current project, which seeks to understand the breakdown mechanism of GaN power Fin-FETs and push their operating limits in high power applications. Specifically, a GaN power Fin-FET model will be developed and simulated in Silvaco Atlas to evaluate the proposed breakdown mechanism theory and find optimized device parameters. Real GaN power Fin-FETs will then be fabricated with these optimized parameters and stressed under different high power experimental conditions to evaluate the design.



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GaN.

Vertical GaN Fin Transistors for RF Applications

2.09

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Sponsorship: DARPA DREaM Project, ARPA-E Switches Project

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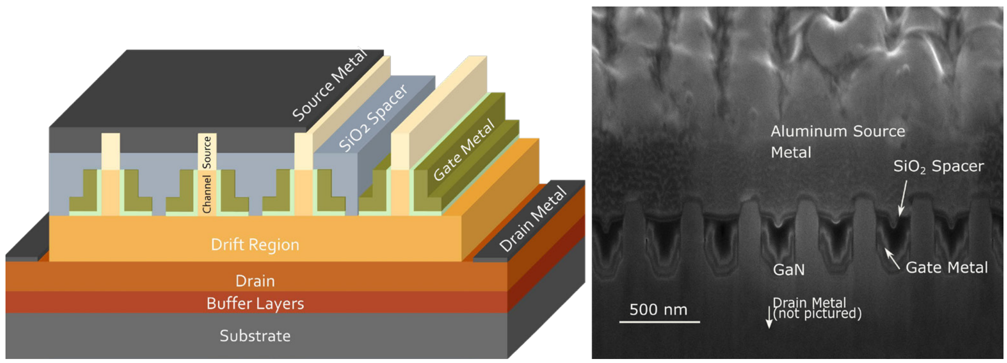
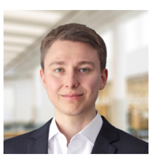
Research Interests:
Electronic devices, electronics, energy, GaN, III-Vs, nanotechnology.

Lateral HEMTs have traditionally dominated the GaN device market, but because they require high current confinement along the surface, they are unable to reach their theoretical performance limits. Here, we present a new vertical device structure for 200 V, 30 GHz applications. This vertical design enables bulk heat dissipation, area independent breakdown, and reduced dependence on surface states for unmatched RF performance.

Using GaN wafers grown with the layer structure shown below, 100 nm wide fins with smooth sidewalls are made with a wet/dry etching technique. A sidewall patterning and spacer technique was developed to make vertical, sub-200 nm gate lengths while avoiding standard photolithography resolution limits. By employing a variable fin width based structure, we are also able to use device-level threshold voltage engineering to study its effects on improving RF device linearity. The final devices will be characterized for their frequency and breakdown performance.



▲ Schematic and SEM cross-section of vertical GaN fin transistor.



Nitrogen-polar Aluminum-nitride-based Field-effect Transistors

2.10

J. Lemettinen, H. Okumura, N. Chowdhury, I. Kim, T. Palacios, S. Suihkonen

Sponsorship: Academy of Finland, JSPS KAKENHI, DARPA DREAM

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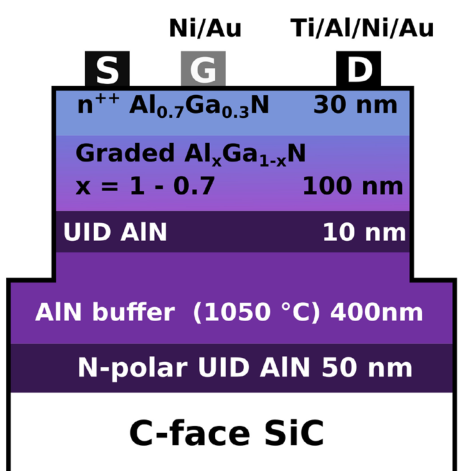
Research Interests:
Electronics, GaN, nanomanufacturing.

GaN-based transistors have shown excellent performance in power amplification and power switching applications. One evolutionary step, nitrogen-polar (N-polar) III-N transistors, exhibit lower contact resistance, greater electron gas confinement, and a lower leakage current than the more widely used metal-polar transistors. N-polar AlN buffer layers are the ideal transistor platform, offering the highest back barrier, the highest thermal conductivity in III-Ns, and lower buffer-leak current. Recently, we demonstrated a smooth N-polar AlN by metal-organic vapor phase epitaxy (MOVPE). We present the optimization of MOVPE growth of nitrogen-polar AlN for high crystalline quality and low unintentional impurity concentration. Using a two-step buffer consisting of layers with low threading dislocation density and low impurity concentration, we demonstrate an N-polar AlN metal–semiconductor field-effect transistor (FET) and a continuously graded AlGaN-channel N-polar polarization-doped FET.



◄ Schematic cross-sectional view of the N-polar AlGaN-channel polarization-doped field-effect transistor (POLFET) on an AlN buffer.

Internal Heat Transfer in Tunnel Diodes at Different Transport Regimes

2.11

J. Xue, Z. Li, R. J. Ram

A tunnel diode or Esaki diode employs quantum-mechanical tunneling to exhibit negative differential resistance, which is typically used as high-frequency oscillators and amplifiers. In this report, we developed ab-initio analytical solutions and applied TCAD simulation tools to examine the internal thermal transport behaviors of such a diode in both low-bias band-to-band tunneling regime and high-bias carrier diffusion regime. Traditionally, tunnel diodes are treated as lumped resistive-heating elements in terms of thermal characteristics. However, here we found different internal heat generation and transfer processes for the two regimes under steady-state operation, and thus producing distinct spacial temperature distributions near the diode junction, even for the case that a device dissipates the same amount of total power under these two regimes. This result could provide key insights in thermal management and thus improve performance and reliability for such devices, as well as tunnel field-effect transistors, multi-junction photovoltaics, and novel nano-structured devices relying on tunneling effects based on either 3-D or 2-D materials.

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Research Interests:
2-D materials, displays, electronic devices, electronics, energy, field-emitter devices, GaN, III-Vs, lasers, light-emitting diodes, nanomaterials, quantum devices.

High-performance Field-emission Cathodes using Trilevel Resist

2.12

N. Karaulac, J. L. Shaw, A. I. Akinwande
Sponsorship: DARPA/MTO INVEST

Cold cathodes based on silicon field emitter arrays (FEAs) have shown promising potential as electron sources in a variety of applications such as e-beam lithography, x-rays, and THz sources. However, FEAs face a number of challenges that have prevented them from achieving the high current, high current density, and long lifetime necessary for commercial applications. One problem limiting the lifetime of FEAs is emitter tip burnout due to Joule heating. The current fabrication process for FEAs results in a non-uniform distribution of emitter tip radii. At a fixed voltage, emitters with a small radius emit a higher current while emitters with a large radius emit a lower current. Therefore, emitters with a small radius reach their thermal limit due to Joule heating at lower voltages and consequently burnout. Previous solutions to mitigating tip burnout have focused on limiting the emitter current with resistors, transistors, or current limiters based on Si nanowires in order to obtain more uniform emission current.

In this work, we focus on increasing the uniformity of emitter tip radii, i.e., reducing the standard deviation, as a means to reduce tip burnout and increase emitter tip utilization. The non-uniform distribution of emitter tip radii first forms during the photolithography step that defines the array of "dots" which become the etching mask for the silicon tips. In our FEA fabrication process, we use a tri-level resist process that nearly eliminates the light wave reflected at the photoresist/silicon interface, and hence improves the uniformity of the dot diameter. Furthermore, we integrate the emitter tips with silicon nanowires to improve their reliability. Our fabrication process results in highly uniform and scalable FEAs with nearly identical B_{FN} and high current ≥ 10 mA.

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Development of a Scanning Anode Field Emission Microscope

2.13

O. Ilori, A. I. Akinwande

Sponsorship: Air Force Office of Scientific Research

Field emitter arrays (FEA) are excellent electron and ion sources, but they have not found widespread adoption in demanding devices such as dynamic pattern generators, THz, RF, Deep UV, X-ray, electron, ion, and neutron sources, where high current (> 1 mA) and long operating lifetime (>10,000 hrs.) are required. One major challenge is the sensitivity of emitted electron and ion current to spatial non-uniformity of emitter tip radii and temporal non-uniformity of work function due to gas adsorption and desorption at the tip surface. These non-uniformities results in the variation of the field enhancement factor (β), a key performance parameter for field emitters and ionizers. β relates the tip electric field to the applied voltage between the gate and the tip. Variation in β results in severe underutilization of the tips. Only few tips with the large β contribute to emission or ionization and these, if not protected, burn-out leading to very short lifetime. Hence more uniform β will lead not only to increase current density, but also long tip lifetime.

We are developing a Scanning Anode Field Emission Microscope (SAFEM) that will be used to characterize the spatial and temporal distribution of the field factor $\beta(x,y,t)$ of FEAs in order to provide a more basic understanding of the operation of FEAs. The equipment will also allow us to study the dependence of $\beta(x,y,t)$ on fabrication process and nozzle techniques for improving $\beta(x,y,t)$ such as thin film coating of tips with metals such as Ir or Pt. The SAFEM is designed to accurately and precisely position an anode over each tip of an FEA to acquire the spatial and temporal distribution of emission tip current $I_{tip}(x,y,t)$ and anode to tip voltage, $V_{AE}(x,y,t)$, and from which a map of field factor $\beta(x,y,t)$ is extracted. The SAFEM opens up a new window to probe fundamental processes in FEA.

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Electronic devices, electronics, field-emitter devices, MEMS & NEMS, nanomaterials, nanotechnology, sensors.

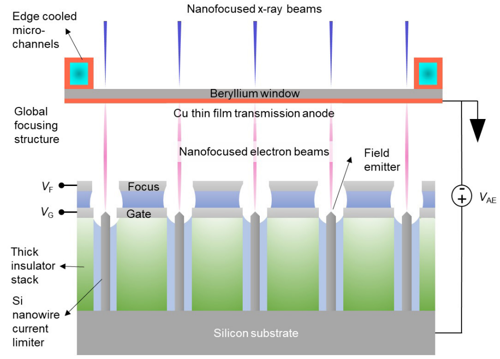
Double Gated Field Emitter Arrays for Nano-focused X-ray Sources

2.14

G. Rughoobur, A. I. Akinwande, A. Goy, K. Arthur, G. Barbastathis, R. Lanza, B. K. P. Horn, W. Krull (MGH), R. Gupta (MGH), H. Eppich

Sponsorship: IARPA/AFOSR

Scalable and high-density Si field emitter arrays (FEAs) are advantageous due to CMOS compatibility, maturity of technology and ability to form sharp tips using oxidation. A Si nanowire current limiter (~200 nm wide, 10 µm tall) is necessary to avoid burning of the sharper tips. In critical applications, a second gate is essential to control the focal spot size of the electron beam as the tips become blunt with time and consequently the turn-on voltage also increases. With the focus electrode, stray electrons extracted by the gate closest to the tip will be captured and only electrons emitted within a certain cone angle will reach the anode, hence achieving a narrower focal spot size compared to a single gated Si FEA. In this work, we are fabricating Si FEAs with the two integrated gates and current limiter for nano-focused electron sources. The narrow electron beam will then be accelerated towards a microchannel-cooled anode with a thin Cu film to generate nano-focused X-ray beams.



◄ Distributed nano-focused X-ray source using silicon field emitter arrays with a focusing gate.

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Research Interests:
Information processing, multimedia, systems.

Machine Learning for Analog Circuit Design

3.01

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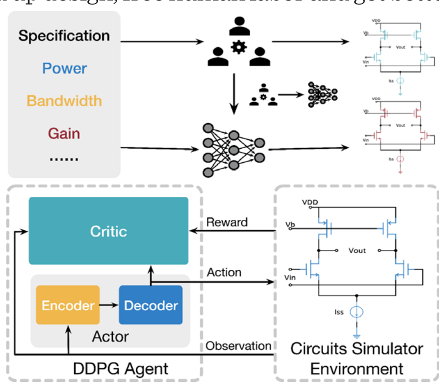
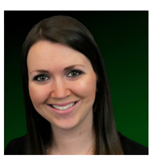
Sponsorship: IBM, QI, SONY, Intel, Samsung, Xilinx, Qualcomm, ARM, AMD, Amazon

Analog circuits process continuous signals. The design process relies on human experts to search for parameters that satisfy circuit specs with their experience and intuitions, which is highly labor intensive, time consuming and suboptimal. We propose Learning to Design Circuits (L2DC) to use reinforcement learning (RL) to optimize circuits. We train an RL agent with no prior knowledge. In one step, L2DC first gets observations, then generates new parameters and gets reward, finally adjusts its strategy. We evaluate L2DC on 2 transimpedance and 2 voltage amplifiers. Trained for a day, our RL agent can achieve comparable or better performance than human experts trained for a semester. It first learns to meet hard-constraints (gain, BW) and then learns to optimize good-to-have targets (area, power). Compared with exhaustive search, L2DC can achieve 250x higher sample efficiency with comparable performance. With L2DC, we can speed up design, free human labor and get better performance.



◄ L2DC System Overview. Actor first generates a set of parameters as its actions by an encoder-decoder sequence-to-sequence model. Then the rewards and observations from the simulator environment are fed back to the RL agent to update design strategy



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Research Interests:
Batteries, electronics, energy, energy harvesting devices & systems, photovoltaics, power management.

A Bidirectional LLC Converter using Common Mode and Differential Mode Current Injection

3.02

J. D. Boles, J. A. Santiago-Gonzalez, D. M. Otten, D. J. Perreault

Sponsorship: Bosch, NSF GRFP

Power converters are ubiquitous in today's world of electronics, and the push for higher power density converters has opened new realms of applications for them. One popular converter topology for high performance, high power density converters is the LLC resonant converter, which relies on the frequency-dependent gain of an LLC network for voltage conversion. This LLC network consists of a capacitor, inductor, and transformer in series, with the transformer's magnetizing inductance serving as the LLC's second inductance. This LLC network's gain characteristic is advantageous because it allows the converter to achieve a wide range of input/output voltage gain with only a narrow range of switching frequencies. However, with a traditional LLC converter, this valuable gain characteristic is only present for power conversion in the forward direction. This is inopportune for bidirectional converters.

In this work, we have demonstrated a converter topology that achieves the LLC gain characteristic during both forward and backward operation. This topology splits the traditional LLC topology into two equal halves, each with half the current-carrying capability. Then, we add an auxiliary inductor between the two inverter switch nodes to serve the magnetizing inductance role during reverse operation. Both halves are driven identically in parallel for forward operation, resulting in common-mode current injection into the LLC resonant tank and no current through the auxiliary inductor. During reverse operation, the two halves are driven 180 degrees apart, resulting in differential-mode current injection that passes through the auxiliary inductor. As a result, the resonant tank exhibits a gain characteristic resembling that of an LLC network in both directions. This topology brings the high-performance of LLC resonant converters to a variety of new applications requiring bi-directional power flow, such as consumer electronics, electric vehicles, and grid energy storage.

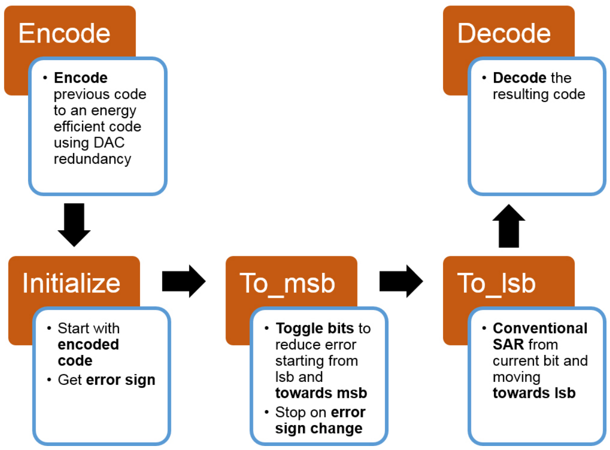
Recode then LSB-first SAR ADC for Reducing Energy and Bit-cycles

3.03

H. S. Khurana, A. P. Chandrakasan, H.-S. Lee

Sponsorship: Center for Integrated Circuits and Systems

Many signals, for example medical signals, do not change much from sample to sample most of the time. Conventional switching scheme for SAR ADCs do not exploit this signal characteristic, and test each bit starting with the MSB. Previous work called LSB-first saves energy and bit-cycles by starting with a previous sample code and searching for the remainder by testing bits from the LSB end. However, certain code transitions consume unnecessary energy even when the code change over previous code is small. This work addresses it by a new algorithm called Recode then LSB-first (RLSB-first) that reduces the switching energy and bit-cycles required for all cases of small code change across the full range of possible previous sample codes. RLSB-first uses split-DAC to systematically encode the previous code before LSB-first. RLSB-first lowers switching energy by up to 2.5 times and uses up to 3 times fewer bit-cycles than LSB-first.



▲ RLSB-first Algorithm

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SHARC: Self-healing Analog Circuits with RRAM and CNFETs

3.04

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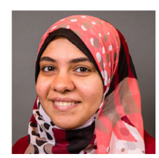
Sponsorship: Analog Devices, Inc.

Carbon nanotube field-effect transistors (CNFETs) and non-volatile Resistive Random-Access Memory (RRAM) enable building energy-efficient mixed-signal systems. However, metallic CNTs (m-CNTs) pose a significant obstacle for CNFET circuits, as they create shorts between CNFET's source and drain and hence the gate does not control their conductivity. This translates into (1) 100x intrinsic gain reduction for analog circuits causing failure of the whole system, (2) high power consumption and degraded noise margin for digital circuits. For VLSI CNFET circuits, the percentage of metallic to semiconducting CNTs must be limited to less than 0.01%, which is hard to achieve by growth techniques. To overcome the remaining m-CNTs problem after growth, we present a new circuit technique called Self-Healing Analog circuitry with RRAM Correction (SHARC). Non-volatile RRAMs are 3D integrated with CNFETs whereas each CNFET is split into multiple minimum width FETs (i.e., "sub-CNFETs"), with a RRAM cell in series fabricated directly under (or over) the source or drain contact of each sub-CNFET.

SHARC is a non-volatile technique that self-reconfigures the circuit by programming RRAMs. The sub-FETs including m-CNTs become connected in series to a high-resistance RRAM that effectively removes those sub-CNFETs from the circuit, while CNFETs containing only semiconducting CNTs are connected in series with a low-resistance RRAM. Post SHARC, a single m-CNT results in a worst-case reduction of amplifier gain of only 3 dB instead of 106 dB before using SHARC. RRAM programming can be performed once for all CNFETs in parallel for larger-scale circuits during fabrication process. We experimentally demonstrate the first and largest CMOS CNFET mixed-signal systems robust to m-CNTs (by implementing SHARC in amplifiers and switches) such as a 4b-DAC and 4b-SAR ADC in a 3 μm technology node. SHARC can also be combined with additional existing circuit techniques to further improve performance.



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Contactless Current Sensing using Fluxgate Magnetometers

3.05

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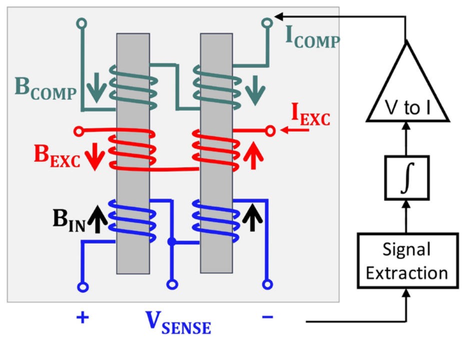
Sponsorship: Texas Instruments

Industries need reliable current sensing solutions for 1) power quality management — to measure real power, reactive power, and distortion, and 2) machine health monitoring — for monitoring, prevention, and diagnosis of faults. We are developing smart connectors with current sensing abilities using integrated fluxgate (FG) magnetic sensors. FG magnetometers offer higher sensitivity and linearity over alternatives. They work by driving magnetic cores in and out of saturation and sensing the resulting differential voltage. We propose a sensor with energy-efficient front-end design to enable FG sensing with a large input range, high sampling rate, and low energy per measurement. We use digitally-assisted analog circuits to push for higher bandwidths and for bandwidth-scalability with duty cycling. The resulting system will offer an energy-efficient solution at both >100 kHz bandwidth for machine health monitoring and <1 kHz for power quality management applications.



◄ Fluxgate sensor with two magnetic cores and three coils: excitation, sense, and compensation. When excited, one core saturates before the other, producing voltage VSENSE as a function of (BIN - BCOMP). Compensation provides feedback for linearity.

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Secure System for Implantable Drug Delivery

3.06

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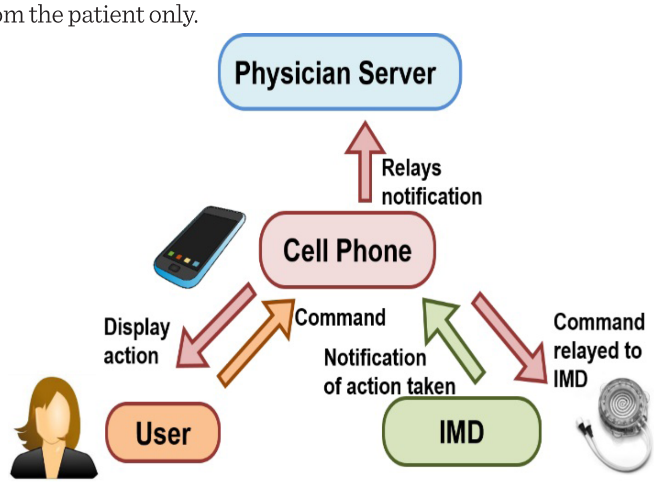
Sponsorship: Analog Devices, Inc.

Implantable drug delivery offers several advantages over conventional oral dosage forms such as site-specific targeted action, better patient compliance and sustained release of therapeutic agent. However, the control of the command to these devices lies with the patient, who can program it as per his/her needs. Thus, any compromise of the controller device/cell phone would render the system ineffective. We propose to solve this problem with a combination of energy-efficient cryptography and relevant physiological signal from user. This makes it very difficult for any attacker, even with significant control over the controller, to break the system as they cannot emulate the response from the user. Hence, with our proposed system, we would be able to protect an implantable drug delivery system by making it respond to only legitimate commands from the patient only.



▲ A generic diagram of an implantable drug delivery system involving all the parties

A Smart THz Identification Tag

3.07

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Sponsorship: Center for Integrated Circuits and Systems, National Science Foundation

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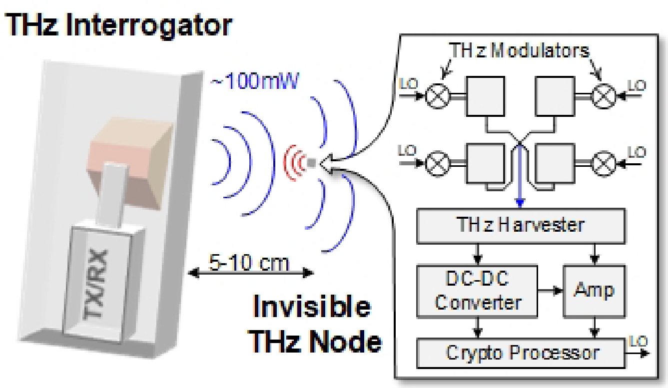
Radio Frequency Identification (RFID) tags have been widely used for counterfeit mitigation, authentication and supply chain management. Small size and power efficiency are important aspects of these tags which are limited by off-chip antenna and packaging. Operating at THz frequency can enable on-chip antenna array within mm-size with sufficient gain. In this work, we implement a fully integrated pad-less 1.4mm^2 tag working at 260GHz. It consists of a multi-functional antenna array, which splits the received signal to feed THz-DC converter and THz modulators, in addition to scattering back the uplink information from the tag. The THz harvester consists of Schottky diode that converts the received signal to DC and extracts the downlink data. A cryptographic processor with a zero-knowledge authentication protocol controls the data communication with the reader in a secure way while consuming 10µW. Thus, THz-ID presents a low-cost and secure solution with competitive read distances.



◄ mm-size THz ID with THz Interrogator

A Low Noise CMOS Molecular Clock using Frequency Initialization based on the Second-harmonic Dispersion Curve of the Absorption Line Profile

3.08

M. Kim, J. Mawdsley, C. Wang, R. Han

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Miniature clocks with high, long-term stability are critical to navigation, sensing and communication networks. Recently, CMOS molecular clocks which use a sub-THz spectrometer to probe the absorption lines of carbonyl sulfide molecules have emerged to achieve a low-cost miniature clock with high, long-term stability. However, molecular clocks require a voltage-controlled crystal oscillator (VCXO) and a fractional-N phase-locked loop (PLL) as a frequency multiplier to generate the sub-THz probing signal, which causes three problems. First, in-band noise is degraded due to the high-frequency multiplication factor of the PLL, because VCXOs can range in oscillation frequency only up to several hundred MHz. Second, fractional spurs generated by a delta-sigma modulator of the PLL further deteriorates the spectral purity of the probing signal. Finally, the bandwidth of the PLL is limited by 1/10 of the VCXO's frequency for the loop stability of the PLL.

In this work, we designed a molecular clock without a VCXO and a PLL to resolve this problem. A sub-THz voltage-controlled oscillator (VCO) is directly controlled by a negative feedback loop and the clock signal is obtained by using frequency dividers following the VCO. Also, the second-harmonic dispersion curve of the absorption line profile was utilized for frequency initialization instead of using a PLL. Since the polarity of the second-harmonic dispersion curve is positive only when the frequency of the probing signal is very close to the absorption line, detection of the absorption line does not depend on the signal strength. Also, the second harmonic signal is robust against spectral baseline variations. By using the proposed frequency initialization method instead of a PLL, the noise performance of the proposed molecular clock is expected to significantly improve. It can also achieve further miniaturization of ultra-stable clock by eliminating the need for a VCXO.

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Electronics, integrated circuits, nanotechnology, photonics, sensors, systems.

Scalable Quantum Vector Magnetometer in 65nm CMOS

3.09

M. I. Ibrahim, C. Foy, D. R. Englund, R. Han

Sponsorship: Center for Integrated Circuits and Systems

Nitrogen-vacancy (NV) centers in diamond have enabled room-temperature vector magnetic field sensing with high sensitivity and spatial resolution with applications in the life sciences, tracking, and metrology. However, current NV sensing apparatuses use bulky off-the-shelf components for the spin state's control and detection, which increase the system's scale. In order to address this challenge, previously we introduced the first hybrid CMOS-NV platform to shrink this spin-based magnetometer to chip scale. We integrated the microwave generation and delivery system, which controls the NV's spin states, and the optical system, which reads these states, into the same CMOS platform. Although we successfully measured the optically detected magnetic resonance (ODMR) of the NVs, the signal to noise ratio of the sensor was limited, which lead to inferior sensitivity. In this work, we present a new scalable CMOS-NV quantum sensor with enhanced sensitivity.

Our scalable magnetometer is enabled by a novel uniform microwave delivery structure, which consists of an array of current-carrying conductors. This uniform array coherently drives the spin states of the NV centers over a larger area, which are subsequently read out optically by the green pump. Thus, this geometry enhances the sensor's sensitivity by increasing the number of NVs addressed. To reduce the shot noise from the green laser, we insert an on-chip optical filter that rejects this green pump. This filter is a three-layer grating structure, where we place a grating layer aligned with the maxima of the green diffraction pattern of the preceding layer. This design offers two orders of magnitude improved rejection compared to our first prototype. In total, the present device improves sensitivity by three orders of magnitude. This work enables a highly scalable and sensitive platform for magnetic tracking, and gradient detection, NMR spectroscopy, and other applications.

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Contactless Power Estimation using Signal Processing and Machine Learning

4.01

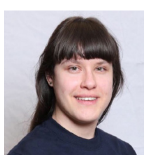
A. Casallas, J. H. Lang
Sponsorship: HARTING, Texas Instruments

Measuring power consumption of electrical systems is a critical task in industrial environments and can be used to monitor power efficiency and machine performance. Currently used contactless methods of power measurement can require time-consuming installations and are expensive and limited in accuracy. We are developing a contactless clip-on sensor that will estimate voltage, current, and power in electric power cables. Our goal is to create a power measurement device that is more accurate, affordable, and easy to install than current state-of-the-art solutions.

We estimate current by using a sensor array to detect magnetic fields around a set of cables. We then digitally process the fields to spatially filter magnetic fields from external sources, such as adjacent power lines or eddy currents. Our goal is to use these signal processing techniques to eliminate the need for shielding around the sensor array, which would increase the device cost. In addition to classical signal processing techniques, we are also training neural nets to explore whether these can generate better estimates.

We estimate voltage by using shielded electrodes that fit snugly around the power cables. Since the digital processing software has access to the full current and voltage estimate waveforms, we can calculate instantaneous power and can measure any phase lag between voltage and current in the system. This can be used to diagnose power inefficacies or unacceptably low power factors in an electrical power system.

At present, our system is estimating current to an accuracy of 0.5%, which is comparable to currently used systems. The device may only cost a fifth of the price of industrial power detection systems, which can sell for upwards of $1000. Although we are still in the process of refining algorithms and hardware, we should soon have a completed system with significant advantages over currently used state-of-the-art systems.



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Fast Monocular Depth Estimation on Embedded Systems

4.02

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Depth sensing is a critical function for many robotic tasks such as localization, mapping and obstacle detection. There has been a significant and growing interest in performing depth estimation from monocular RGB camera images, due to the relatively low-cost, size, weight and power of cameras. However, state-of-the-art depth estimation algorithms are based on fairly large deep neural networks, which have high computational complexity and energy consumption. This poses a significant challenge when performing real-time depth estimation on an embedded platform, for instance, mounted on a Micro Aerial Vehicle (MAV).

Our work addresses this problem of fast depth estimation on embedded systems. We investigate efficient and lightweight encoder-decoder network architectures. To further improve their computational efficiency in terms of real metrics (e.g., latency), we apply resource-aware network adaptation (NetAdapt) to automatically simplify the proposed architectures. In addition to reducing encoder complexity, our proposed optimizations significantly reduce the cost of the decoder network, which has not been previously explored. We target real-time inference on the Jetson TX2 embedded platform to enable deep learning-based depth estimation onboard miniaturized vehicles.

AMC: AutoML for Model Compression and Acceleration on Mobile Devices 4.03

Y. He, J. Lin, Z. Liu, H. Wang, L.-J. Li, S. Han

Sponsorship: IBM, QI, SONY, Intel, Samsung, Xilinx, Qualcomm, ARM, AMD, Amazon

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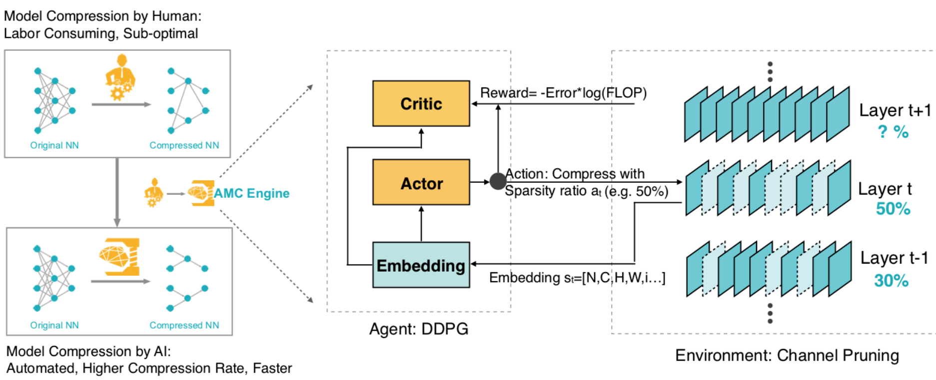
Model compression is a critical technique to efficiently deploy neural network models on mobile devices which have limited computation resources. Conventional model compression techniques rely on hand-crafted heuristics and rule-based policies that require domain experts to explore the large design space, which is usually sub-optimal and time-consuming. In this paper, we propose AutoML for Model Compression (AMC) which leverages reinforcement learning to provide the model compression policy. This learning-based policy outperforms conventional rule-based policy by having higher compression ratio, better preserving the accuracy and freeing human labor. Under 4x FLOPs reduction, we achieved 2.7% better accuracy than the hand-crafted compression policy for VGG-16 on ImageNet. We applied this automated compression pipeline to MobileNet and achieved 1.81x speedup of measured inference latency on an Android phone and 1.43x speedup on the Titan XP GPU, with only 0.1% loss of ImageNet accuracy.



▲ Overview of AutoML for Model Compression (AMC) engine

Low Power Depth Estimation for Time-of-Flight Imaging 4.04

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Sponsorship: Analog Devices, Inc.

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Depth sensing is used in a variety of applications that range from augmented reality to robotics. One way to measure depth is to use a time-of-flight (TOF) camera, which obtains depth by emitting light and measuring its roundtrip time. TOF cameras are appealing because they obtain dense depth maps with minimal latency. However, for reasons that range from system power constraints to multi-camera interference, it is not always possible to measure depth maps in real-time. To overcome this issue, we propose an algorithm that leverages concurrently collected images to estimate depth without illuminating the scene. Images are routinely collected in many applications, and our goal is to reuse them to estimate depth.

Our technique uses the 2D pixel-wise motion of the images, or the optical flow, to estimate the 3D motion in the scene and obtain a new depth map. Using this strategy, we show that we can estimate the depth of rigid objects, objects undergoing non-rigid deformations, and multiple independent rigid objects in a general scene. To ensure that the total system power for depth sensing is reduced, we also account for the power of the computation and design our algorithm to run efficiently on low power embedded platforms. These platforms have limited compute resources and present a challenge in estimating dense depth maps in real-time. We overcome these challenges by exploiting our problem set-up to simplify the depth estimation process. We evaluate our algorithm on both synthetic and real data and show that we can obtain accurate depth maps in real-time, demonstrating that our approach is feasible for mobile applications.

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HAQ: Hardware-aware Automated Quantization

4.05

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Sponsorship: IBM, QI, SONY, Intel, Samsung, Xilinx, Qualcomm, ARM, AMD, Amazon

Model quantization is a widely used technique to compress and accelerate deep neural network (DNN) inference. Emergent DNN hardware accelerators begin to support flexible bit width (1-8 bits) to further improve the computation efficiency, which raises a great challenge to find the optimal bit width for each layer: it requires domain experts to explore the vast design space trading off among accuracy, latency, power, and model size, which is both time-consuming and sub-optimal. Conventional quantization algorithm ignores the different hardware architectures and quantizes all the layers in an uniform way.

In this paper, we introduce the Hardware-Aware Automated Quantization (HAQ) framework which leverages the reinforcement learning to automatically determine the quantization policy, and we take the hardware accelerator's feedback in the design loop. Rather than relying on proxy signals such as FLOPs and model size, we employ a hardware simulator to generate direct feedback signals to the RL agent. Compared with conventional methods, our framework is fully automated and can specialize the quantization policy for different neural network architectures and hardware architectures. Our framework effectively reduced the latency by 1.4-1.95x and the energy consumption by 1.9x with negligible loss of accuracy compared with the fixed bit width (8 bits) quantization. Our framework reveals that the optimal policies on different hardware architectures (i.e., edge and cloud architectures) under different resource constraints (i.e., latency, power and model size) are drastically different. We interpreted the implication of different quantization policies, which offer insights for both neural network architecture design and hardware architecture design.

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Algorithms and Low Power Hardware for Keyword Spotting

4.06

M. Wang, A. P. Chandrakasan

Sponsorship: Foxconn Technology Group

Keyword spotting (KWS) is widely used in mobile devices to provide hands-free interface. It continuously listens to sound signals, detects specific keywords and triggers the downstream system. Since it is always on, achieving low system power consumption is of vital importance. Moreover, considering the overall system performance and user experience, high KWS accuracy must be provided. A KWS system should avoid mis-triggering the downstream system, which is usually much more power consuming and responds promptly to user's commands. The algorithm based on convolutional neural network (CNN) delivers high accuracy with a small model size that can be stored fully on-chip. However, the state-of-the-art neural network (NN) accelerators either target at complex tasks using large CNN models or only support limited NN architectures which cannot deliver high classification accuracy for KWS.

In this work, we take an algorithm and hardware co-design approach to implement a low power NN accelerator for the KWS system that is able to process small-medium CNNs with flexible structures. Several techniques are proposed to minimize overall energy consumption. A fully-integrated KWS system with a feature extraction block, an NN accelerator and a posterior handling unit will be implemented on-chip.

Passive Artificial Synapse Arrays for Neuromorphic Systems

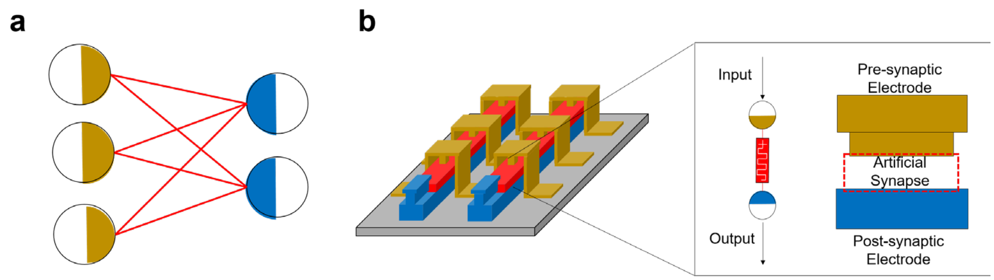
4.07

S. H. Tan, C. Choi, Y. Park, P. Lin, H. Yeon, S. Choi, J. Kim

Sponsorship: IBM, Samsung, SenseTime, NSF

Useful AI algorithms perform "learning" by optimizing parameters to execute a specific task. In modern computers, learned parameters known as synaptic weights are processed in ALU's and stored in DRAM. However, frequent storage and retrieval of weights limit speed and efficiency of CMOS-based systems. Neuromorphic systems are promising alternatives since they rely on analog artificial synapses that store trainable synaptic weight values as material conductance states constituent where artificial neurons cross.

Here, we experimentally demonstrate passive systolic arrays of artificial synapses that can learn and process information for AI-related tasks. Potentiation voltage pulses raise synapse conductance, while depression pulses reduce conductance. For backpropagation and inference, sub-threshold voltage inputs are weighted by synapses and summed as current along output columns. Hence, these arrays can passively compute weighted summations, which are the core operation of AI.



▲ a) Synapses in an artificial neural network (lines) retain information about the connection strengths between neurons (circles) to perform computations. b) A 2 x 3 systolic array implements the network illustrated in (a).

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Simulation of the Effects of Shot Noise on Optical Neural Networks

5.01

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Modern neural networks are incredibly computationally complex, requiring millions of FLOPS for single image recognition. The use of neural networks within data centers requires considerable energy, which will only increase as neural networks usage increases. One proposed solution to energy consumption in neural networks is optical neural networks. Optical neural networks are optical devices which allow for neural networks to be used for both inference and training. Optical neural networks are bounded in energy consumption by the lowest amount of photons per operations allowed by the standard quantum limit (SQL), which is determined primarily by shot noise. We present the results of many simulations of injecting shot noise into different neural network configurations. These results allow us to better understand what types of neural networks are robust to the noise of optical neural network configurations, and how to design optical neural networks so that they consume lower energy.

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Nonvolatile Reconfigurable Photonic Integrated Circuits

5.02

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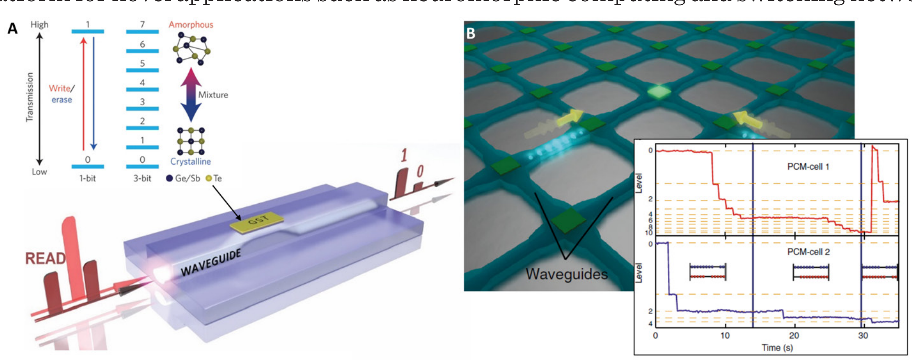
Sponsorship: DARPA Extreme program

The integration of nonvolatile phase-change materials (PCMs) in photonic circuits enabled low-energy, highly cyclable optical switches, phase-shifters, and multilevel memories, in addition to the demonstration of a photonic synapse and in-memory computing. These experimental results used evanescent fields or external laser radiation as switching mechanisms, which are challenging to scale up for architectures comprising hundreds of active cells. To tackle the scaling challenge, we present a hybrid optoelectronic approach based on a CMOS scalable process. We use transparent heaters for simultaneous electro-thermal switching of the PCM and low-loss optical modulation by evanescent-field coupling of the guided mode. Our results are crucial for the development of architectures able to retain a given configuration with no power consumption, which benefits any on-chip active photonic system and provides a platform for novel applications such as neuromorphic computing and switching networks.



▲ Schematic of an all-optical Integrated multilevel non-volatile memory enabled by a controllable mixture of crystalline and amorphous $Ge_2Sb_2Te_5$, the most widely used PCM.

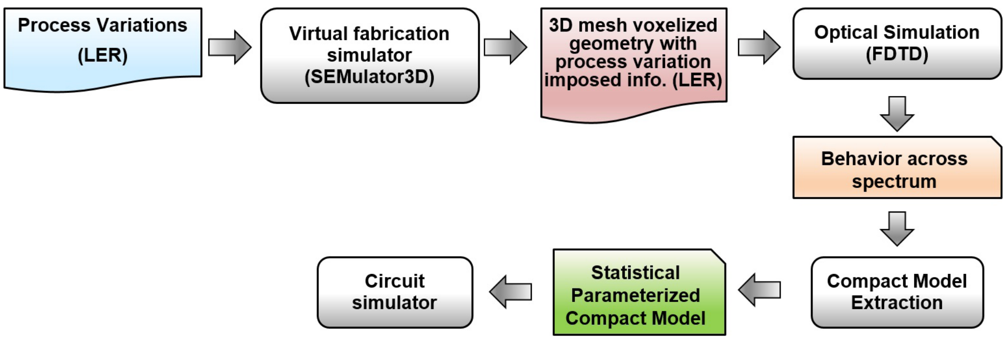
Y-Branch Compact Model Including Line Edge Roughness Effect

5.03

S. I. El-Henawy, D. S. Boning
Sponsorship: AIM Photonics

With the booming silicon photonics as design platform, it is crucial to provide compact models that would help designers, enhance yield, and serve as a building block in the silicon photonics PDK. We develop a compact model for Y-Branch that specifies the variations in the transfer characteristics against line edge roughness (LER) which is a statistically random process variation.

This model provides the transmission mean and variance as a function of LER parameters, amplitude (A) and correlation length (CL), across the spectrum of interest. The modeling flow is shown in the figure below. We start by simulating different A and CL combinations with multiple instantiations for each. The optical behavior of the structure with imposed LER is extracted and used to develop a statistical parameterized compact model. This model can be used in the photonic integrated circuit (PIC) simulators to predict the performance across process variations and worst corner-cases as the models we rely upon in CMOS design.



▲ Simulation flow used to develop a statistical compact model that includes LER effect.

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Photonics.

Slot Antennas for Graphene Mid-IR Photodetectors

5.04

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Sponsorship: Institute for Soldier Nanotechnology

Mid-infrared imaging has a wide range of applications, such as night vision, surveillance, and remote chemical sensing. However, the current options for mid-IR imagers leave much to be desired, with cooled detectors offering excellent performance at the cost of power, size and system complexity, while uncooled bolometers struggle with slow response times and low detectivity. Graphene is a promising alternative mid-IR sensitive optoelectronic material due to its broadband absorption, strong electrical response and wide process compatibility, but its low absorption for normally incident light poses a challenge in designing high efficiency devices.

We propose to couple the graphene with metal slot antennas, compact resonators which capture specific wavelengths of light and significantly enhance the free space to graphene light coupling efficiency. Additionally, since the antennas' footprints are much smaller than their absorption cross sections, multiple antennas with different resonant frequencies can be placed in close proximity, allowing broadband and spectrally selective photodetection. Here we present simulations confirming the validity of our approach as well as measurements of early stage slot antennas demonstrating consistency between simulated and measured optical properties. We will also discuss how the antenna absorbers can be engineered into actual photodetectors as well as paths forward for integrating the technology with electronics. This research paves the way towards establishing graphene as a viable mid-IR sensing technology, improving upon the response time of bolometers and adding spectral selectivity while maintaining similar detectivities.

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2-D materials, communications, nanomaterials, nanotechnology, optoelectronics, photonics, sensors.

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Research Interests:
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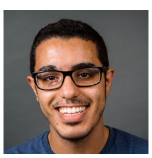
Optical Neural Networks with Low-energy Data Movement using Fourier Holography

5.05

L. Bernstein, R. Hamerly, A. Sludds, D. R. Englund
Sponsorship: Natural Sciences and Engineering Research Council of Canada

In recent years, the vast performance gap between artificial deep neural networks (DNNs) and biological neural networks has rapidly narrowed in fields such as image and speech recognition, translation, and prediction. DNNs' surge in popularity is largely due to advances in computing power such as GPUs and the availability of large datasets for training. But despite their transformative impact, DNNs today face many challenges, including high power consumption and slow speed. It is becoming clear that DNNs may run far more efficiently on specialized accelerator hardware, and there are many efforts underway in industry and academia to develop customized electronic DNN accelerators (e.g., ASICs, TPUs, FPGAs and mixed-signal circuits). There is special emphasis on reducing the cost of data movement, as this accounts for the largest consumption of energy in DNNs by an order of magnitude or more. Matrix multiplication and convolution, central to DNN computations, are particularly power-hungry in this regard since the same input elements must be accessed from memory repeatedly in the computation of output elements.

We present a new DNN hardware accelerator leveraging optics as opposed to electronics to greatly reduce the energy cost of data movement in matrix convolution. In this optical neural network, a single memory read of the matrices to be convolved is required. Once accessed and broadcast with a micro-LED array, data are fanned out (i.e., copied to multiple outputs) using Fourier holography. Electronic detector units can then perform local multiplications and additions, completing the convolution operation. In this way, by taking advantage of the passive routing capabilities of optics, the redundant memory access of conventional processors can be avoided. Thus, energy savings of up to an order of magnitude can be achieved, allowing for DNN computations of greater complexity and reduced cost.



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Research Interests:
Communications, displays, electronic devices, electronics, III-Vs, integrated circuits, lasers, light-emitting diodes, optoelectronics, photonics, photovoltaics, sensors, Si, SiGe and Ge, spintronics.

Photonic Crystal Enhanced Silicon Photodetector as Near-IR Sensors

5.06

E. Al Johani, A. Atabaki, R. J. Ram
Sponsorship: MIT Energy Initiative

The increase in demand on efficient near-infrared (NIR) sensors for light ranging (LIDAR), thermal-cameras, and soon, free-space optical communications requires a more low-cost and scalable alternative to the state-of-the-art detectors. The use of NIR range to send and receive information between objects in short-ranged environments, while maintaining eye-level safe emissions, is one the biggest challenges for free-space photonics. Silicon is becoming the most widely-used material in fiber-based communication for its integrability with the electronics world. Leveraging the advanced complementary metal-oxide-semiconductor (CMOS) technology to the free-space world is the focus of this work. We present a more cost-effective alternative to the current III-V detectors; we implement photonic crystal cavity (PhCC)-enhanced detectors in CMOS-compatible polycrystalline silicon.

The indirect bandgap of crystalline silicon, however, poses some optical limitations. An indirect bandgap material requires momentum exchanges with every photon interaction that lowers its absorption probability. Further, low-energy photons rely on sub-bandgap transitions to mediate full-absorption. Current methods use light-resonating structures to recycle and stimulate photon absorption. By adding a 2D-PhC resonator layer, we are able to confine surface-illuminated light into a 5μm diameter region with great intensity, leading to a higher effective path-length and improved detector responsivity. More than 1000 variants of this detector are implemented in a 65nm CMOS process. We find the most optimized designs using a bi-sectional method on the different variants and experimentally characterize the devices. FDTD models of the PhCC structures are used in conjunction to aid design and validate PhCC behavior. We report polysilicon PhCC-enhanced sensors with Q-factors of 6500 resulting in responsivities at 1300nm up to 0.13mA/W; a 25x improvement over non-resonant surface-illuminated Silicon detectors.

Computational Raman Thermography

5.07

Z. Li, R. J. Ram

Sponsorship: SMA SMART program

Raman imaging can be used to resolve the chemical composition, strain, and temperature of various materials. For example, people estimate the channel temperature of HFETs using the Raman spectra and the result is much more reliable than using electrical analysis. However, the techniques, which are usually referred as Raman thermography, are not widely applied in nanoscale temperature measurements because of the relatively low spatial and temperature resolutions, which are several hundred nanometers and 1 K, respectively.

In this report, we apply a suite of computational tools to the problem of Raman imaging. The associated statistical and computational techniques include de-noising, deconvolution, and Bayesian inference. In our pipeline, we first apply optimization algorithms to eliminate the Poisson noise in our Raman spectrum. After de-noising, statistical techniques including Bayesian inference are used to infer physical parameters for materials using the entire Raman spectra. In addition to improving the sensitivity and specificity of materials characterization, we can improve the achievable spatial resolution with deconvolution algorithms to achieve sub-diffraction resolution.

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2D materials, batteries, electronics, III-Vs, information processing, lasers, light-emitting diodes, MEMS & NEMS, nanomaterials, nanotechnology, optoelectronics, photonics, photovoltaics, power management, spintronics, thermal structures, devices & systems.

Zero Change CMOS Photonics for Telecommunications Applications

5.08

M. de Cea, A. H. Atabaki, R. J. Ram

Sponsorship: DARPA POEM

Large-scale photonic integration is crucial for scaling telecommunications and data-communications systems to address the ever-increasing data rate requirements of modern communications. By allowing monolithic integration of electronics and photonics, unmodified CMOS process based-systems provide an unmatched advantage in terms of overall system cost, scalability and potentially performance. Nevertheless, its use at wavelengths above 1.2μm has been limited by the small thickness of the silicon device layer (<100nm) and the lack of a strong absorbing material.

In this work, we fabricate and characterize a zero-change CMOS resonant modulator designed to avoid strong radiation losses at 1550nm, showing a 14GHz 3dB bandwidth. A slightly negative chirp parameter is measured, which is beneficial for long distance transmission. These results demonstrate the potential for the use of unmodified CMOS processes with a thin silicon device layer for telecommunications applications, which can result in a significant improvement in cost and power consumption.

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Optical Emulation of Integrated Circuits X-ray Tomography

5.09

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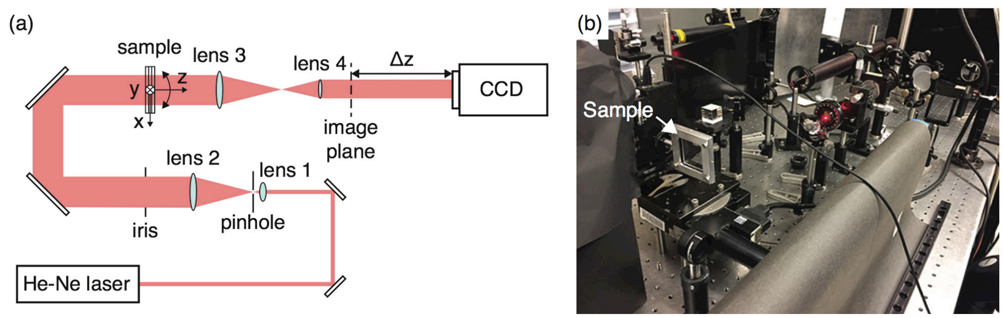
Sponsorship: IARPA/AFOSR

Inspection of integrated circuits (ICs) is a crucial component of chip security and X-ray tomography happens to be a method of choice. We propose to use nano-focused X-ray sources based on double-gated Si field emitters for that purpose. In this work, we experimentally emulate the X-ray imaging system in the visible range in order to test the reconstruction procedure. The sample is a multi-layer glass phantom that is a 104scale up of an actual IC design. The light source is a 0.6 micron CW laser emulating a spatially coherent X-ray source around 17keV. The intensity of the diffraction pattern is measured on a CCD camera for different position of the sample and we use a gradient descent method to produce an approximation of the three-dimensional structure of it. A deep neural network then produces a final reconstruction from the approximation. We show successful reconstruction of a 4 layer sample with illumination angles as low as 10°.



▲ (a) Optical setup. A collimated laser beam illuminates the sample mounted on a 2-axis rotation stage. The light is allowed to diffract over a distance Δz from the image plane in order to emulate X-ray free space propagation. (b) Actual optical setup.

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Integrated Visible-light Liquid-crystal Phase Modulator

6.01

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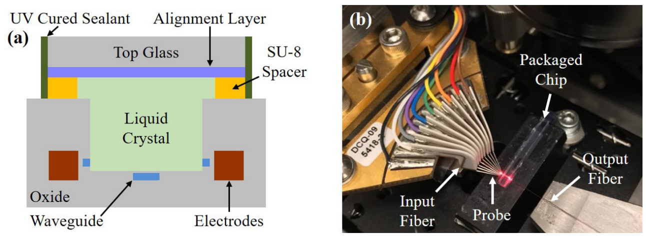
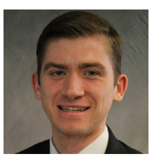
Sponsorship: DARPA VIPER program, NSF Graduate Research Fellowship

Integrated photonics systems at visible wavelengths have many wide-reaching potential applications, including image projection systems, underwater optical communications, and optogenetics. Generally, these visible-light integrated systems are based on silicon-nitride waveguides since silicon nitride has a low absorption coefficient within the visible spectrum and is CMOS compatible. However, silicon nitride has a low thermo-optic coefficient and does not exhibit significant electro-optic properties, which makes integrated phase tuning at visible wavelengths a challenge.

As a solution, nematic liquid crystals, with strong birefringence in the visible spectrum, can be integrated and used for phase modulation. In this work, an integrated visible-light liquid-crystal phase modulator is experimentally demonstrated with 36π phase shift within ±3V in a 500-μm-long modulation region. This compact phase shifter will enable low-power small-form-factor integrated systems at visible wavelengths.



◄ (a) Cross section of device, consisting of a silicon-nitride waveguide, liquid crystal deposited into an oxide trench, a top glass chip with an alignment layer, and metal electrodes. (b) Photograph of the packaged chip and experimental setup.



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Ultra-thin, Reconfigurable, High-efficiency Meta-optical Devices in mid-Infrared

6.02

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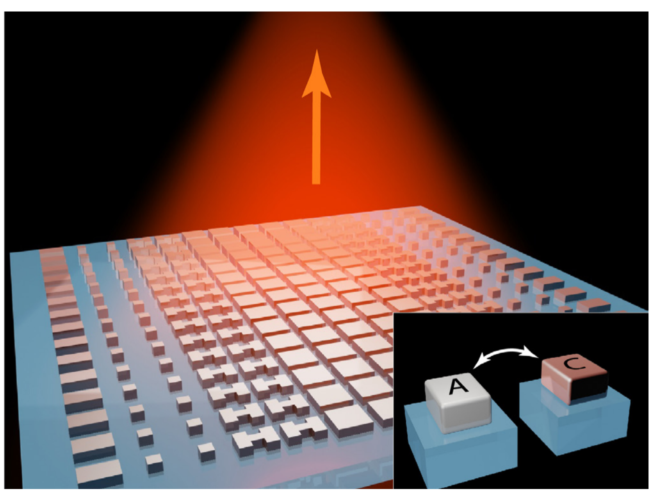
Sponsorship: DARPA EXTREME Program

The mid-infrared (MIR) is a frequency band strategically important for numerous biomedical, military, and industrial applications. Further development of MIR devices is hindered by the lack of inexpensive and efficient basic optical elements, such as lenses, wave plates, filters, etc. Furthermore, the available components are typically bulky and passive. Our research addresses these challenges by leveraging novel low-loss optical phase-change materials (Ge-Sb-SeTe) and their sub-wavelength patterning to achieve ultra-thin (thickness < $\lambda_0/8$), high-efficiency (>40%), and multi-functional MIR components. As a proof-of-principle, we demonstrated a reconfigurable filter and a bifocal meta-lens with a switchable focus. We believe that our findings will enable new range of compact, multi-functional spectroscopic and thermal imaging devices.



◄ Illustration of reconfigurable meta-lens, which properties can be switched by transitioning non-volatile phase-change material (GeSbSeTe) from amorphous (A) to crystalline (C) state.

CMOS-compatible Optical Phased Arrays Powered by Monolithically-integrated Erbium Lasers

6.03

J. Notaros, N. Li, C. V. Poulton, Z. Su, M. J. Byrd, E. S. Magden, E. Timurdogan, C. Baiocco, N. M. Fahrenkopf, M. R. Watts

Sponsorship: DARPA E-PHI program, NSF Graduate Research Fellowship

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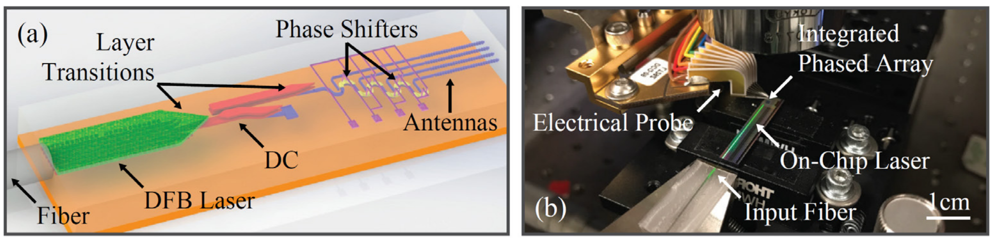
Lasers, nanotechnology, optoelectronics, photonics.

Integrated optical phased arrays (OPAs), fabricated in advanced silicon photonics (SiP) platforms, enable dynamic high-speed control of free-space light. As such, OPAs have many promising wide-reaching applications, including light detection and ranging (LIDAR), holographic displays, and free-space communications. However, due to the absence of a direct-bandgap material in standard SiP platforms, many of these demonstrations have been limited to systems with fiber-coupled off-chip lasers, which restrict the practicality of the system due to packaging and cost concerns.

In this work, an erbium-doped laser and an electrically-steerable OPA are monolithically integrated into a CMOS-compatible 300-mm-wafer SiP platform. This system represents the first demonstration of an active CMOS-compatible SOI photonics system powered by a rare-earth-doped monolithically-integrated laser and paves the way for future monolithic SiP systems, such as data communication links and optical synthesizers.



▲ (a) Simplified schematic (not to scale) and (b) photograph of the integrated optical phased array system powered by a monolithically-integrated erbium laser.

Large-scale Deep Optical Neural Networks with Coherent Detection

6.04

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Sponsorship: IC Postdoc Fellowship

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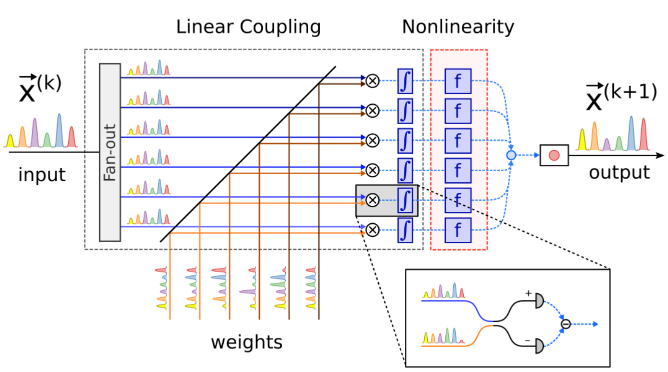
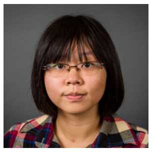
Research Interests:
Information processing, lasers, nanotechnology, optoelectronics, photonics, quantum devices, Si.

Progress in deep learning has led to a resource crunch where performance is limited by computing power, which is in turn limited by energy consumption. Optics can improve the speed and energy consumption of neural networks, but current schemes suffer from limited connectivity and the relatively large footprint of low-loss nanophotonic devices. We present a novel approach based on homodyne detection that circumvents these limits and is scalable to large (millions of neurons) networks without sacrificing speed (GHz) or energy consumption (sub-fJ/operation). Here the inputs and weights are both encoded optically, allowing the system to be reprogrammed or trained on the fly. Simulations using pre-trained digit-classification models reveal a standard quantum limit (SQL) to energy consumption, in the range of 10-100 zJ/operation, which is below the thermodynamic (Landauer) limit. This architecture will enable a new class of ultra-low-energy processors for deep learning.



▲ Schematic diagram of a layer in the neural network. Optical interference and homodyne detection (inset) perform the matrix multiplication for connections (grey box). The nonlinearity is computed in electronics (red box).



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Research Interests:
Displays, light-emitting diodes, optoelectronics, organic materials.

Solid-state Photon Upconversion Based on Triplet-triplet Annihilation: Towards Application

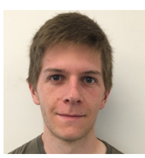
6.05

T.-A. Lin, M. Wu, M. C. Sherrott, V. Bulović, M. A. Baldo
Sponsorship: Department of Energy

Photon upconversion, a non-linear optical process to convert low-energy photons into higher energies, has many applications in fields including photovoltaics, infrared sensing, and bio-imaging. Specifically, upconversion through triplet-triplet annihilation (TTA) in organic molecules can be achieved under low power, making the applications realistic. Furthermore, developing solid-state upconversion systems enables flexibility in device design while avoiding damage to the device with which it is being integrated. In this work, we demonstrate two examples of solid-state upconversion systems based on TTA that are feasible for practical applications.

Integration of an infrared-to-red upconversion device with photovoltaics promises to improve the achievable efficiency beyond the conventional theoretical limit. Previously, we have demonstrated solid-state infrared-to-red upconversion with a bilayer device consisting of colloidal nanocrystals and an organic dye (rubrene). To improve the performance of this system, we further designed an optical cavity that substantially increased the absorption of incident light in the absorbing layer. This enabled us to reduce the incident threshold power to a level lower than terrestrial solar flux, making such a device ready for integration with photovoltaics.

On the other hand, integrating green-to-blue upconverters with green organic light emitting diodes (OLEDs) introduces a new avenue towards stable and efficient blue OLEDs. Solid-state systems via reliable deposition techniques such as thermal evaporation are imperative for uptake of the technology into commercial applications. Herein, we adopt thermal evaporation compatible materials in the upconverters and, for the first time, demonstrate green-to-blue upconversion in evaporated films. Our work offers a pathway for upconversion towards application and its potential for addressing challenges faced by current optoelectronic devices.



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Research Interests:
MEMS & NEMS, nanomanufacturing, nanotechnology, photonics, quantum devices.

Strain Tuning for Scalable Entanglement of Defect Centers in Diamond

6.06

I. Harris, N. Wan, T.-J. Lu, D. R. Englund
Sponsorship: Massachusetts Institute of Technology

Quantum information systems are an important emerging technology in the fields of communication, simulation, and computation. Defect centers in diamond are one of the most promising candidates for quantum memories due to their long coherence times and convenient optical readout. Entanglement, a resource required for quantum information processing, can be created by interfering the single photon emissions of two defect centers, this requires that the photons be of the same wavelength for realistic detectors. Since defect centers are generally subject to random strain and electric fields that affect their emission wavelengths, interference-based entanglement protocols are not possible without active tuning of the defect. We present simulations and preliminary experimental results of MEMS devices to strain tune diamond defect centers and route their emissions for entanglement protocols. These defect tuning devices can be incorporated in future quantum information processing and communication systems for scalable entanglement.

Lithium Niobate Integrated Photonics in the Visible Spectrum

6.07

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Sponsorship: NSF

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Research Interests:
Communications, displays, electronic devices, electronics III-Vs, lasers, light-emitting diodes, nanomaterials, optoelectronics, quantum devices, Si, SiGe and Ge, thermal structures, devices & systems, UV photonics.

A key feature in the success of integrated photonics has been the robust set of materials in the infrared which exhibit desirable optical properties. For example, lithium niobate offers large second-order nonlinearities and an electro-optic effect, and silicon leverages highly-scalable fabrication techniques. Work over the past several years has shown enormous promise for devices at visible wavelengths, particularly compact sensors and metrology tools, where silicon is not transparent. Progress on visible-wavelength integrated photonics has suffered from the lack of comparable materials which provide both low optical loss and an electrical tuning mechanism.

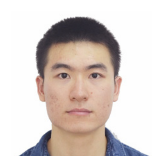
We discuss one method for extending lithium niobate integrated photonics into the visible spectrum. Silicon nitride is deposited on thin-film lithium niobate and patterned to define the photonic structures. A key feature is the simple fabrication which requires no direct etching of the lithium niobate, while retaining access to its high second-order nonlinearity. Mode confinement is simulated to be over 50% in the infrared (1550 nm) and 77% in the visible (674 nm). We demonstrate visible-wavelength modulators and microring resonators with high-quality factors in the infrared. These structures form the basis of many optical circuits; we discuss conventional and exotic applications such as frequency synthesis for atomic, molecular, and optical physics applications with an eye toward fully-integrated atomic clocks.

Particle Defect Yield Modeling for Silicon Photonics

6.08

Z. Zhang, M. B. McIlrath, D. S. Boning

Sponsorship: AIM Photonics



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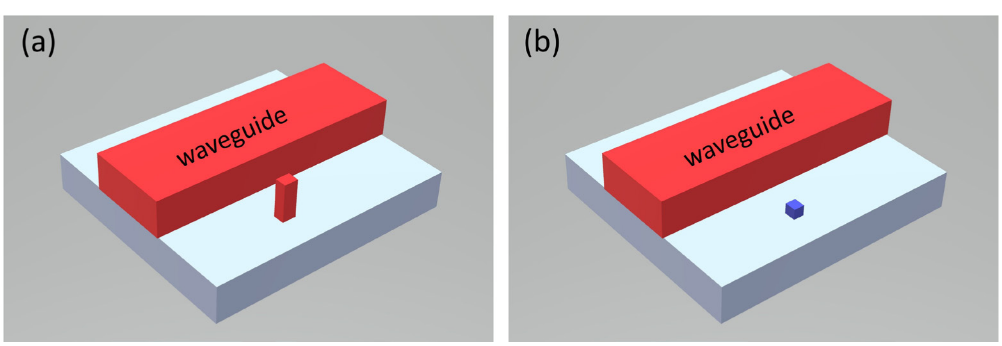
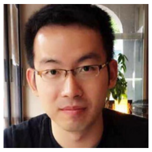
Research Interests:
Integrated circuits, numerical method, photonics.

As a promising design platform for various applications, silicon photonics now needs mature process variation models for manufacturing design. One of the many process variations is particle defect, which can arise in photolithography, deposition, etch, and other processes, and can cause significant impact when it is in proximity to the device component.

We present a study of the impact of two different types of particle defects on straight waveguides and Y-splitters. We modify and apply the adjoint state method, which is widely used in optimization to accelerate the speed of simulation and reduce numerical error. The model and results will be used to help generate layout design rules and critical area extraction methods, and help silicon-photonics designers to predict and optimize yield of complex silicon-photonics devices and circuits.



▲ Modeling of particle defects in proximity to a straight waveguide: (a) silicon pillar photolithography defect, and (b) metal cube for foreign metal particle.



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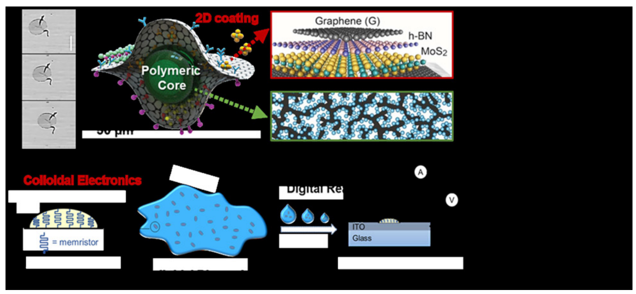
2-D materials, biological devices & systems, energy, energy harvesting devices & systems, medical devices & systems, molecular & polymeric materials, nanomaterials, nanotechnology, organic materials, transducers.

The Design and Fabrication of Colloidal State Machines

7.01

P. Liu, A. T. Liu, D. Kozawa, J. Dong, M. Saccone, V. B. Koman, S. Wang, Y. Son, M. H. Wong, M. S. Strano
Sponsorship: AFOSR-MURI

Arming nanoelectronics with mobility and self-awareness opens new opportunities in environmental monitoring and biomedical sensing. To date, examples of nanoelectronics with mobility and on-board logics remain elusive. I will discuss how the growing library of 2-D-soft material composites has facilitated the symbiotic engraftment of electronics onto mobile colloidal particles, thus paving the way towards next-generation microrobotics with low energy consumptions. Specifically, I will focus on our recent efforts in synthesizing such 2-D-macromolecular heterostructures, one following the conventional top-down lithographic approach, and the other using a novel fabrication technique named autoperforation, owing to the spontaneous perforation of the grafted 2-D materials around a pre-designed polymer template. These two methods, together, lay the foundation of building the proposed colloidal state machines.



◄ Schematic illustration (right) of the interior structure of a typical colloidal state machine, showing the polymer-2-D material interface.

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Optical and Structural Properties of Two-dimensional Semiconductor by Cathodoluminescence in Scanning Transmission Electron Microscopy

7.02

H. Lee, A. Singh, S. Gradečak
Sponsorship: SMART, Samsung Scholarship

Atomically thin two-dimensional transition metal dichalcogenides (TMDs) are semiconducting materials with bandgaps in the visible spectral range, which makes them promising for future optoelectronic applications. Various types of structural defects have been observed in exfoliated and synthesized 2-D TMDs crystals. They significantly affect their optical properties. However, the roles of the defects are not fully understood. For example, contradicting roles of sulfur vacancies in TMDs have been reported (either enhance or degrade photoluminescence). It could be because of the limited length scale of optical characterization to the micrometer scale. Using electron beam-induced luminescence (cathodoluminescence) will overcome this size limit and provides optical and structural information simultaneously. In addition, it will enable high-resolution direct correlation of them.

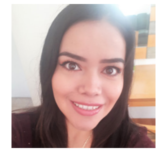
We, for the first time, present cathodoluminescence from tungsten disulfides and molybdenum disulfides using scanning transmission electron microscopy (STEM). To enhance the luminescence from monolayer TMDs, they are sandwiched by hexagonal boron nitride (hBN) with higher energy gap. We observed inhomogeneous luminescence map due to the imperfect interface between TMDs and hBN. This provides information of interface quality between layers in nanometer-scales. Furthermore, proper condition to measure cathodoluminescence such as temperature and voltage will be presented. This work will introduce cathodoluminescence-STEM as a useful technique to characterize fine TMD heterostructures and their interface quality on a nanometer scale.

Carbon Nanotube Based-field Emitters by 3-D Printing

7.03

I. A. Perales-Martínez, L. F. Velásquez-García

Sponsorship: MIT-Tecnológico de Monterrey Nanotechnology Program



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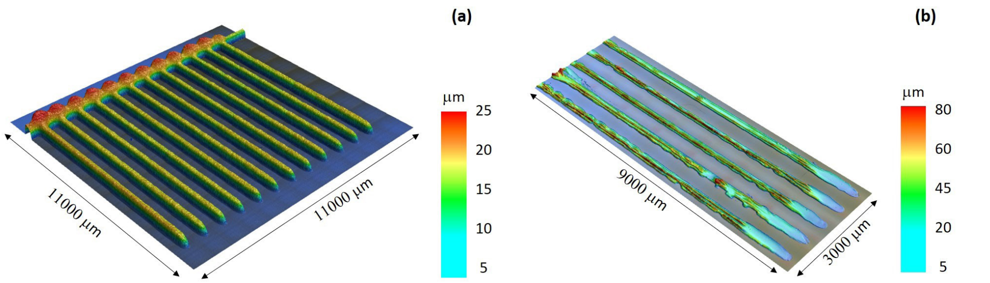
Research Interests:
Field-emitter devices, nanomaterials.

Electron sources are essential in many vacuum devices such as amplifiers and X-ray sources. Field emission cathodes based on carbon nanotubes (CNTs) are very attractive due to CNT's properties, e.g., high aspect ratio, excellent mechanical and chemical stability, and high current emission density. To achieve high current emission, devices with a plurality of unshielded CNTs are required, which is typically obtained via expensive and time-consuming cleanroom microfabrication. This project explores the use of direct ink writing (DIW) to create low-cost CNT field emission cathodes. As is shown in the figure below, the proposed printed device has a network of silver traces (as gate electrode) and CNT composite traces (as emitting electrode). Current research efforts focus on optimizing the formulation of the CNT ink to print as many possible numbers of emission sites. The proposed methodology offers a promising route to achieving field electron sources with high current densities.



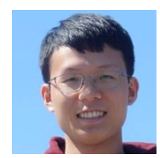
▲ Confocal microscopy image of surface topography for DIW-printed traces of (a) silver ink and (b) CNT ink using a 225 mm nozzle

Strong Coupling between Cavity Photons and Nano-ferromagnet Magnons

7.04

J. T. Hou, L. Liu

Sponsorship: Air Force Office of Scientific Research



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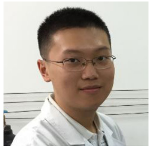
Available from June 2021.

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

Coupled cavity-magnon systems have recently received great attention as a novel platform to realize strong light-matter interactions with potential applications in quantum information processing. So far, coherent coupling has been demonstrated between ferrimagnetic yttrium iron garnet (YIG) samples and microwave cavities with various designs. As the coupling strength $g \propto \sqrt{N}$, where N is the spin number in the magnetic material, bulky ferromagnets (with millimeter dimensions) had to be employed for reaching strong coupling. Here we report magnon-photon coupling between lithographically patterned planar superconducting resonators and Permalloy (Py) samples, thereby reducing the effective mode volume of resonators we can achieve strong coupling even in nanometer size ferromagnets.

We pattern superconducting niobium films into coplanar waveguide (CPW) resonators and deposit nanometer thick Py wires on top of the resonators. An in-plane magnetic field is applied to adjust the resonance frequency of the Kittel mode in Py, which interacts with the resonator mode to create mode splitting near resonance. By fitting the resonance mode's evolution, we confirmed the scaling of g with N by varying the Py sizes. To further lower N, we employ low-impedance resonators which greatly enhance the magnetic field near the Py wires. A g/2pi of 41MHz is obtained for 20µm × 2µm × 10nm Py, corresponding to 2x1010 spins. Compared with previous works, our experiment shows a more than 6 order of magnitude reduction in spin number. The high coupling strength with nanomagnet can enable electrical control of magnon-photon coupled system, where the damping can be tuned by a DC current through spin Hall effect. Our results open up the possibility of realizing lasing operation with magnetic dynamics and will provide a tunable platform to study non-Hermitian physics.



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Research Interests:
Electronic devices, magnetism, spintronics.

Mutual Control of Coherent Spin Waves and Magnetic Domain Walls in a Magnonic Device

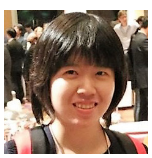
7.05

J. Han, P. Zhang, J. T. Hou, L. Liu
Sponsorship: NSF

Spin waves, the collective excitation of electronic spins inside magnetic materials, offer new opportunities for wave-based computing. Here we experimentally demonstrate mutual interactions between spin waves and magnetic domain walls, where the magnetic domain walls manipulate the phase and magnitude of spin wave and a strong spin wave, in turn, moves the position of magnetic domain walls. The discovery of mutual control between spin wave and magnetic domain wall can lead to efficient mechanisms for modulating spin wave propagation, which opens up the possibility of realizing all-magnon-based reading/writing devices.

In the first part of this work, we experimentally demonstrate that nanometer wide magnetic domain walls can be used to manipulate the phase and magnitude of coherent spin waves in a non-volatile manner. Coherent spin wave is excited and detected in [Co/Ni] multilayers, the perpendicular magnetic anisotropy and relatively low damping factor of which allows the coexistence of domain walls and zero-field coherent spin wave excitation. By comparing the transmitted signals of the spin wave in a device with and without a domain wall, we observe a more than 10 dB change in magnitude and a nearly 180° shift in phase when the spin wave passes through the domain wall.

In the second part of this work, we observe that the domain wall moves opposite to the spin wave propagation direction and reaches maximum efficiency at the spin wave resonance frequency, which is consistent with the picture of spin transfer torque from magnon spin current. The combination of these two effects can potentially provide a platform for realizing efficient spin wave-based memory, computing, and information processing that lie in single spin wave domain.



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Research Interests:
2-D materials, electronic devices, electronics, energy, nanomaterials, nanotechnology, optoelectronics, photovoltaics.

Large-area Graphene Transfer

7.06

W. S. Leong, H. Wang, J.-Y. Hong, J. Kong
Sponsorship: AFOSR FATE MURI

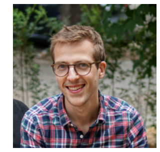
Scalable production of large-area graphene for subsequent device fabrication is important for real-world applications, and chemical vapor deposition (CVD) is now the most widely used approach to obtain large-area graphene. Nevertheless, the performance and reliability of CVD graphene are often limited by the presence of wrinkles and the transfer-process-induced polymer residue.

Here, we report a transfer approach using paraffin as a support layer, where low chemical reactivity and non-covalent affinity to graphene enable transfer of wrinkle-less and clean large-area graphene. The paraffin-transferred graphene has smooth morphology and high electrical reliability with uniform sheet resistance with ~1% deviation over a centimeter-scale area. Electronic devices fabricated on such smooth graphene exhibits electrical performance approaching that of intrinsic graphene with small Dirac points and high carrier mobility (hole mobility =14,215 cm^2/Vs; electron mobility = 7,438 cm^2/Vs), without the need of further annealing treatment. We anticipate that the transfer technique presented in this work is applicable for other 2-D materials and useful for integration of 2-D materials for ubiquitous electronics.

Building Flexible, Microscopic Sensor Nodes with 2-D Materials

7.07

M. Hempel, E. McVay, J. Kong, T. Palacios
Sponsorship: Air Force Office of Scientific Research



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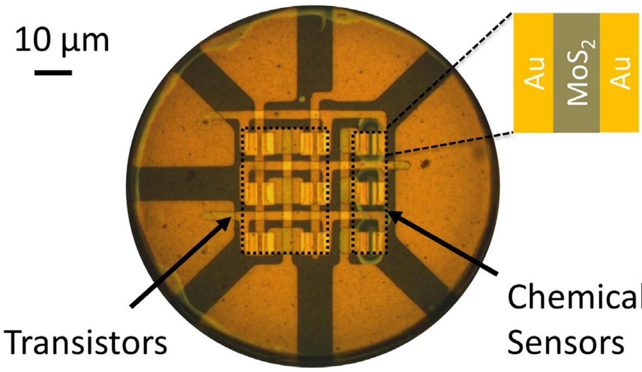
Research Interests:
2-D materials, electronics, integrated circuits, nanomanufacturing, nanomaterials, nanotechnology.

Most sensors in use today are of macroscopic dimensions. However, making sensors smaller than the diameter of a human hair could enable a new paradigm where sensors move in air or liquid and replace expensive permanent installations. This way, for example, tiny sensors could directly monitor the pipes systems of industrial plants to detect leaks or corrosion from the inside. To achieve this goal, we build microscopic sensor nodes, called synthetic cells or SynCells that consist of 100-µm-wide and 5-µm-thick SU-8 polymer disks. The SynCells have a chemical sensor and transistors, which are made of a single atomic layer of molybdenum disulfide (MoS_2). Over the last year, we improved our process to release the SynCells from the fabrication substrate reliably. We also demonstrated state-of-the-art MoS_2 transistor performance and yield and showed high sensitivity of the chemical sensors to amine gases. Our results pave the way for cheap, ubiquitous sensing using microscopic sensors.



▲ Micrograph of a 100-µm-wide SynCell with three chemical sensors and six transistors to detect analytes in solution or air.

Investigating the Role of Hemi-wicking Surface Structures on Critical Heat Flux During Pool Boiling

7.08

Y. Song, Y. Zhu, D. J. Preston, Z. Lu, E. N. Wang
Sponsorship: Exelon Corporation

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

Pool boiling has received significant interest for its ability to passively dissipate high heat fluxes by harnessing the large latent heat of vaporization. Current research on boiling is focused on how to extend the critical heat flux (CHF) limit due to its importance in system efficiency and safety. The most common strategy is texturing of boiling surfaces, and the mechanism of CHF enhancement has been explained by a static force balance of a bubble. Recently, it has been suggested that the dynamics of the contact line can also play an important role for CHF. In particular, an experimentally measured strong correlation between wickability and CHF has attracted significant attention. The direct relationship between the wickability and CHF is becoming a widely-accepted theory.

Although previous studies showed a distinct relationship between wickability and CHF, in this work, we show the applicability of this theory based on the accumulated data of previous studies and experimental data is not always true. We fabricated silicon pillar structures with different dimensions by conventional microfabrication process. First capillary pressure and permeability of surfaces were calculated to characterize wickability. Pool boiling experiments on silicon pillar structured surfaces were performed later to measure CHF values. We found that there is no distinct relationship between the CHF and wickability contrary to a general notion. Our results suggest that although liquid wicking has been found to be important, the parameter wickability defined by previous works alone is not sufficient to describe CHF. In addition to the wickability, we propose that there may be other important parameters that also change along with the surface structures. This work has important implications in the careful prediction of CHF in high flux applications including heat exchangers, nuclear reactors, and integrated circuits.

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Research Interests:
Electronic devices, energy, energy harvesting devices & systems, integrated circuits, MEMS & NEMS, nanomanufacturing, nanotechnology, power management, Si, thermal structures, devices & systems.

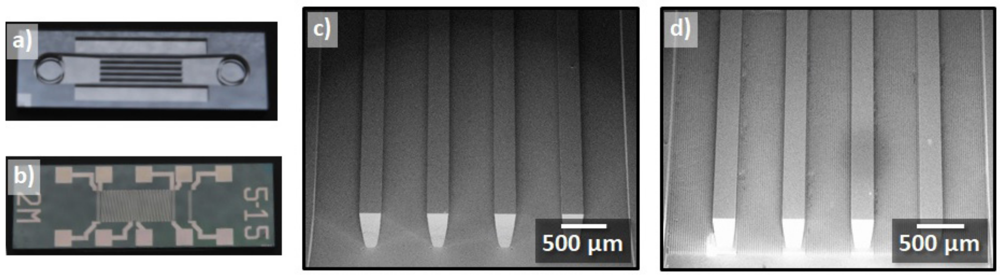
Surface Structure Enhanced Intrachip Multichannel Flow Boiling of 1-Methoxyheptafluoropropane (HFE-7000)

7.09

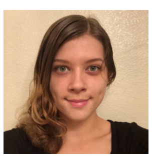
J. Sircar, Y. Zhu, D. Antao, S. Rao, T. Zhang, E. N. Wang

Microchannel flow boiling is capable of meeting the thermal management requirements of high heat flux in integrated circuits but is limited by instabilities that are exacerbated when there are multiple channels in parallel. Surface microstructures have been shown to suppress these instabilities and enhance heat transfer when boiling water. Hydrofluoroethers are dielectric fluids that are industry approved for electronics cooling, but have significantly poorer thermophysical properties with respect to boiling water. Here, we investigate the enhancement of surface microstructures using hydrofluoroethers in multichannel devices.

We fabricated microchannels in silicon with and without micropillars on the heated bottom wall. Our preliminary results show a heat transfer coefficient enhancement with a structured microchannel compared to a smooth microchannel as high as 40%. The results suggest that microstructures can enhance the two-phase heat transfer in microchannels even when using hydrofluoroethers.



▲ Images of fabricated microchannel with micropillar array. Optical images of the (a) front and (b) backside of a tested device. SEM micrograph cross-section of a (c) smooth and (d) micropillar structured multichannel device.



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Research Interests:
2-D materials, electronic devices, photonics, quantum devices, spintronics.

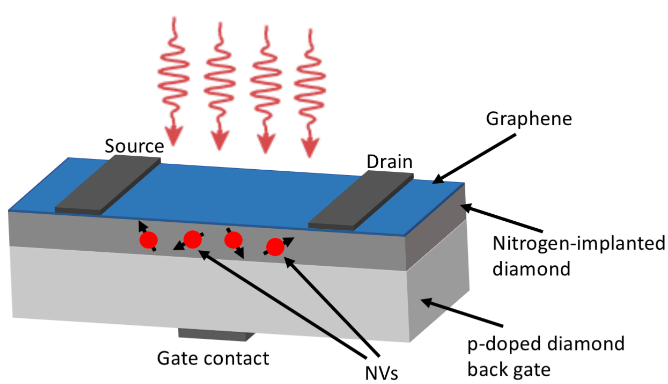
Imaging Hydrodynamic Charge Flows in Graphene

7.10

S. Muschinske, L. De Santis, M. Trusheim, D. R. Englund

Sponsorship: NSF, DOD

Graphene — an atomically thin crystal of carbon — has exceptional material and electro-optic properties that make it a highly promising platform for next-generation logic devices. Electronic transport in graphene is theorized to be dominated by "electron fluids," but these electron fluids have been thus far unobserved as they can only be identified by spatially mapping the charge currents in the material. To directly observe such local phenomena, we propose to develop a "quantum imager" that uses nitrogen-vacancy centers (NVs) embedded in diamond as highly sensitive magnetometers. This system is well-suited for examining local current phenomena as the atomic size of the NV allows us to measure the magnetic field with sub-nanometer spatial resolution, permitting us to use an array of NVs to create a precise spatial map of the current in graphene. This quantum imager will elucidate the nature of transport in graphene and enable the development of ultra-low power dissipation devices.



▲ Proposed quantum imager.

Stable Deep-blue Luminescent Colloidal Lead Halide Perovskite Nanoplatelets

7.11

S. K. Ha, C. M. Mauck, W. A. Tisdale

Sponsorship: U.S. Department of Energy

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Research Interests:
2-D materials, displays, light-emitting diodes,

Recently, colloidal lead halide perovskite nanocrystals have emerged as promising semiconductor nanomaterials due to their spectral tunability, facile processability, and bright emission with high color purity. In particular, strong quantum and dielectric confinement make atomically thin colloidal lead bromide perovskite nanoplatelets a favorable candidate for next-generation deep-blue-emitting (λ_{max} = 437 nm) materials. However, poor photostability poses a critical challenge; they suffer from photobleaching or transformation into thicker, less-confined nanostructures with red-shifted emission upon UV irradiation.

In this work, we synthesize deep-blue-emitting organic-inorganic hybrid perovskite nanoplatelets (Formula: $L_2[ABX_3]BX_4$, L: butylammonium and octylammonium, A: methylammonium or formamidinium, B: lead, X: bromide) with large lateral dimension (~1 μm) by ligand-assisted reprecipitation and systematically investigate the factors that affect the photostability of those nanoplatelets. Photobleaching is found to result from intrinsic instability of the perovskite lattice against UV irradiation in nanoplatelets while transformation into thicker nanostructures results from extrinsic factors—moisture, primarily. Furthermore, we observe that substitution of the organic cation from formamidinium to methylammonium and addition of excess alkylammonium bromide ligands significantly enhances the intrinsic stability of these nanoplatelets. Lastly, we demonstrate that the drop-cast film of methylammonium lead bromide nanoplatelets with excess ligands shows dramatically improved stability both under UV irradiation and under ambient conditions. This study expands our understanding of the factors that affect perovskite nanoplatelet photostability and opens up new possibilities for the fabrication of stable perovskite-nanoplatelet-based optoelectronic devices.

Effects of Beam-induced Carbon Deposition on Electron Energy-loss Spectroscopy Analysis of Compositional Fluctuations in InGaN/GaN Quantum Well LEDs

7.12

S. Goodman, A. Singh, Z. Zhao, D. Su, K. Kisslinger, R. Armitage, I. Wildeson, P. Deb, E. Stach, S. Gradečak

Sponsorship: Department of Energy, Singapore-MIT Alliance Research and Technology

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Research Interests:
2-D materials, GaN, III-Vs, light-emitting diodes, nanomaterials, plasmonics.

InGaN/GaN quantum well (QW) LEDs have high efficiencies and demonstrate wide bandgap tunability, but state-of-the-art InGaN-based LEDs cannot yet be incorporated on-chip. These devices are grown on sapphire instead of Si, due to the large (17%) lattice mismatch between GaN and Si. Fabrication of InGaN/GaN LEDs on Si requires a thorough understanding of the impact of defect formation on device performance. Electron energy-loss spectroscopy (EELS) in the scanning transmission electron microscope (STEM) provides compositional information and electronic properties of a material at the sub-nm scale, and is thus well-suited for investigating the relationship between defects and device performance. However, to conduct accurate compositional analysis using EELS, it is critical to obtain imaging conditions that do not induce artifacts in the sample, including knock-on damage or beam-induced carbon deposition.

We use an aberration-corrected STEM at low accelerating voltage to map the composition of high-efficiency InGaN/GaN QW LEDs using EELS with high spatial resolution. By performing a series of EELS scans with varying beam dwell times and step sizes, we investigate the impact of beam-induced carbon deposition on the compositional analysis obtained through EELS. An artificial decrease in In signal along the EELS scan is observed when the spectrum image is collected at high electron doses. We attribute this artifact to an increase in the intensity of multiple scattering plasmon peaks corresponding to carbon, which are present due to the increased thickness of the carbon layer deposited by the electron beam. Here, we optimize spectroscopic parameters to reduce carbon deposition and produce pristine EELS spectra unaffected by artifacts.

Although carbon contamination particularly impacts characterization of InGaN due to the spectral proximity of the C signal to the In signal, this work applies to other high-resolution EELS studies that require precise quantification.

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Research Interests:
Nanomaterials, quantum devices.

Characterization of MoSi Thin Film Superconductor for Superconducting Nanowire Single-photon Detectors

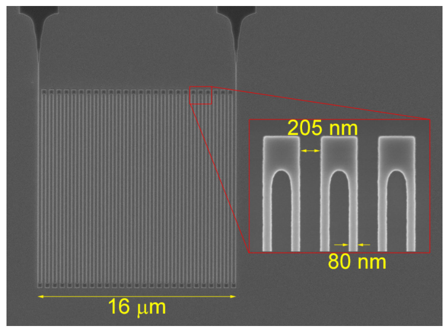
7.13

Y. Morimoto, A. E. Dane, K. K. Berggren

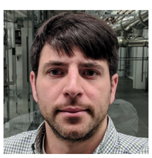
Sponsorship: Skoltech

All electromagnetic signals are comprised of photons. Detecting and manipulating single photons is a key to quantum mechanical approaches to improving communication. Superconducting nanowire single-photon detectors (SNSPDs) have many benefits: the ability to detect infrared photons with nearly 100% detection efficiency, ~20 pS timing precision, and >100 Mcps count rates. Early SNSPDs were made from polycrystalline niobium nitride, but grain boundaries and defects limit device performance. Recently, amorphous materials have been used to fabricate SNSPDs with excellent device performance and yield.

In this work, we studied amorphous molybdenum silicide (MoSi) films. Varying the Mo:Si ratio yielded a maximum transition temperature (Tc) of 7.1 K for a ~20 nm-thick film. The inter-relationship between film thickness, Tc, and sheet resistance could be explained by theoretical models. Understanding how to control the superconducting properties of MoSi films will contribute to improving SNSPDs.



◄ SEM image of a SNSPD wire design patterned with electron beam on HSQ for lithography. HSQ was coated on a MoSi film with Si capping layer.



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MIT.nano Project Updates: Preparing for Phase 1

7.14

N. Menounos, W. R. Hess, K. Payer, D. Grimard

Sponsorship: MIT.nano

The MIT.nano Operations team has been diligently planning for the "Phase 1" relocation, installation, and start-up of Fab.nano, the fabrication toolset component of the lab. To ensure continuity of existing research within MTL and across campus, MIT.nano is taking a proactive approach to code compliance, reducing future environmental impacts, formalizing construction methodology, and pre-facilitation of the infrastructure.

Point-of-use abatement selection: Research in Fab.nano will utilize fluorinated greenhouse gases and numerous hazardous process gases. To reduce carbon dioxide equivalent (CO_2e) emissions and increase safety, many of the vacuum pump effluents will be treated by point-of-use abatement systems. We will discuss the process of selecting an abatement technology, the potential impact on MIT.nano's air emissions, and how this ties into optimizing the tool layout.

Electrical safety review of existing tools: The National Electric Code and OSHA require that all equipment installed within a facility undergo an "examination of equipment for safety". To meet this requirement, many jurisdictions require that a Nationally Recognized Testing Laboratory (e.g., UL and TUV) label the equipment. Much of the Phase 1 toolset is existing legacy equipment that doesn't fulfill this requirement. To address this gap, MIT.nano is piloting an in-house hazard assessment process to identify electrical safety improvements and work with local agencies to create an alternative compliance path.

Project delivery methodology: MIT.nano is executing a formal design-bid-build project delivery method to improve design transparency, define the project scope, and minimize disruption to research by enabling pre-facilitation. We will present a sample of the equipment layouts, isometric drawings, process flow diagrams, and electrical plans, including a draft schedule, tool list, and capabilities.

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Research Interests:
2-D materials, electronic devices, energy, energy harvesting devices & systems, lasers, MEMS & NEMS.

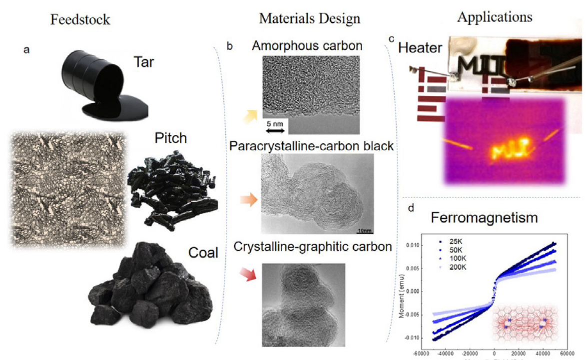
Laser Ablated Natural Carbonaceous for Thin-film Electronics

8.01

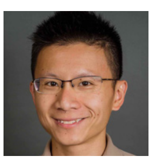
X. Zang, N. Ferralis, S. Ingersoll, J. G. Grossman
Sponsorship: ExxonMobil, DOE

Recycling natural carbonaceous feedstocks for alternative applications beyond burning will help the petroleum/coal industry find a way to use their byproducts or waste. The current decline in energy generation from coal frees up its use for the development of new technologies using either coal or coal-derived byproducts such as tar and pitch. Natural carbonaceous feedstocks can be engineered to produce thin films for electronics with highly tunable electronic properties.

Developing a laser ablation/doping technique will endow natural carbonaceous materials with tunable electromagnetic properties including conductivity and ferromagnetism. Such a technique will enable the application of carbon materials in "clean" applications with extremely low-cost (i.e., coal for 0.05$/kg). Applications include voltage generation on the water-carbon interface, low-cost transistors, and flexible/stretchable. Furthermore, the laser process will also afford large scale and roll-to-roll manufacturing.



◄ Natural carbonaceous materials can be converted to crystalline or amorphous carbon materials. The laser ablated/doped carbon materials have broad applications from transparent electronics to and ferromagnetic devices.



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Research Interests:
2-D materials, colloids, energy, molecular & polymeric materials, nanomanufacturing, nanomaterials, nanotechnology, photonics.

Direct-write Freeform Colloidal Assembly

8.02

A. T. L. Tan, J. Beroz, M. Kolle, A. J. Hart
Sponsorship: NSF

Assemblies of colloidal particles exhibit unique collective behaviors based on particle geometry, composition and arrangement, which enables tailored design of novel materials for diverse applications. Methods to deposit and self-assemble ordered particle solids from suspension are typically limited to fabrication of films and patterns and commonly utilize surface tension to confine particles against substrates. In contrast, direct-write methods to build 3-D structures rely on cohesion between particles in high-density suspensions to achieve structural rigidity, but this precludes particle ordering.

Here, we present a method to build freestanding structures from self-assembled colloidal particles. The structures have mm-cm scale dimensions and can be freeform with aspect ratios > 10, yet retain polycrystalline order. We derive a scaling law that governs the rate of assembly, show how macroscale structural color can be tailored via the size and crystalline ordering of polystyrene particles, and build exemplary freestanding structures using silica and gold particles. Owing to the diversity of colloidal building blocks and means to control their interactions, direct-write assembly could, therefore, enable novel composites, photonics, electronics, and other materials and devices.

Machine Learning for Manufacturing: Anomaly Detection, Nonlinear Dynamics and Beyond

8.03

H. Chen, D. Grullon, M. DeLaus, D. S. Boning

Sponsorship: MIT-IBM Watson AI Lab, SenseTime/Quest for Intelligence

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Research Interests:
Computer-aided design, electronic design automation, nanomanufacturing.

Manufacturing is a crucial driver for our competitiveness and economic growth, and manufacturing industries are poised for transformation based on application of artificial intelligence. Advanced manufacturing facilities are increasingly equipped with many sensors supporting monitoring of the process and equipment, as well as continuous inspection of the generated products. For example, with manufacturing inspection tools, high-resolution images (optical, SEM, and other modalities) of products can be generated and used for further analysis, including defect detection, performance prediction, etc. Taking advantage of the large volume of data available as well as of the recent advancements in machine learning, our goal is to apply and extend machine learning algorithms, such as clustering and classification, to perform anomaly detection in processes, facilities, and products. Also, with the rapid development of Internet-of-Things (IoT) and sensor technologies, advanced manufacturing processes and facilities are becoming highly instrumented, with an enormous number and variety of data streams.

We develop deep learning and Kalman Filter based algorithms to learn the nature behind the manufacturing processes' complex dynamics using the sensor data. Additionally, machine learning model trained on one tool (e.g., one plasma etcher) may be applied to other tools by transfer learning. For prediction on a new similar tool where the data distribution may be different, we may not be able to directly use our model from the old tool, but rather need to combine our old knowledge with new information and transfer our old model to the new tool or domain. Similar techniques can also improve learning in a concept drifting environment, where due to subtle changes in the manufacturing process, the underlying probability distributions of the data are expected to change over time. We envision our research having a large impact on a broader area of physical analytics and IoT solutions.

Direct-write Assembly of Three-dimensional Colloidal Crystals with Structural Color

8.04

E. Chang-Davidson, A. T. L. Tan, J. Tan, A. J. Hart

Sponsorship: MIT UROP Office, MIT Energy Initiative, NSF

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Research Interests:
Nanomanufacturing.

The popularity of 3-D printing has exploded in the last few years as printers have become more reliable and affordable. However, current 3-D printing technology is limited in both materials selection and color. Commercially available 3-D printers only allow a few materials, mostly plastics, and color is produced by adding pigments. In contrast, structural color, or color produced by the arrangement of particles in a material, is both more durable and less toxic. A promising new technology to create structural color in printed materials was developed by the Hart Group at MIT.

This new technology uses direct-write colloidal assembly to print mm- to cm-scale colloidal crystals with controllable structural color. Previously, this technique was limited to one dimension of control over the printing process, but here we present extensions of this work to multi-dimensional control over the final shape of colloidal crystals that exhibit structural color. The method presented is capable of producing mm- to cm- scale structures with repeatable and controllable mm-scale details in all three dimensions. These crystals exhibit structural color based on a threshold value for a constant incorporating printing conditions and material. Being able to control all three dimensions of the printing process allows this technology to become a true 3-D printing technique capable of producing a vast array of different shapes and colors using a variety of underlying materials. The potential applications of this process are many, including new and more efficient small sensors, generators, and solar cells.

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2-D materials, electronics, energy, energy harvesting devices & systems, nanomanufacturing, nanomaterials, nanotechnology, optoelectronics, photonics, photovoltaics.

Vapor Transport Deposition for High-efficiency Perovskite Solar Cells

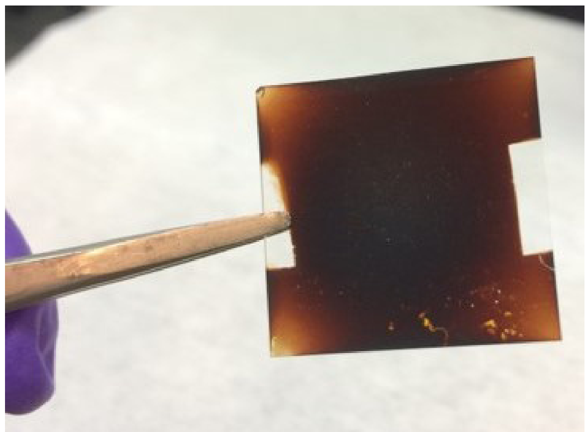
8.05

E. Wassweiler, A. Panda, M. Horantner, V. Bulović

Sponsorship: NSF, Tata-MIT GridEdge Solar

Perovskite solar cells merge a flexible, lightweight structure with high device efficiency. Vacuum processing promises to be a method for creating high-quality and large area perovskite films. Most high-efficiency vacuum deposited perovskite films are made through thermal evaporation. Thermal evaporation, while giving high-quality films, is a slow process.

In our custom-built setup, we deposit perovskite films over a large area with a deposition rate much higher than thermal evaporation. Unlike thermal evaporation, vapor transport deposition relies on a carrier gas to increase material usage and deposition rate. By precisely controlling not only the evaporation of material, but flow of the carrier gas and temperature of the substrate, the morphology and growth rate of thin films can be modified. Here, we demonstrate high-quality, large area perovskite films that grow at a rate orders of magnitude faster than thermal evaporation.



◄ Perovskite film deposited through vapor transport deposition

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Research Interests:
MEMS & NEMS, nanomanufacturing, nanotechnology, Si, systems, thermal structures, devices & systems.

Structural Analysis of Critical-angle Transmission Gratings

8.06

J. Song, R. K. Heilmann, A. R. Bruccoleri, M. L. Schattenburg

Sponsorship: NASA SAT fund

Critical-angle transmission (CAT) gratings are ultrahigh aspect ratio (200-nm pitch, 4 um deep), freestanding X-ray silicon gratings developed to measure scientifically important high-resolution X-ray spectra of astrophysical sources. They are fabricated out of (110)/(100) silicon-on-insulator wafers. The gratings are patterned on the device layer side via interference lithography, followed by deep-reactive ion etching (DRIE). Honeycomb structures are patterned in the handle layer via DRIE, and thin grating membranes are released by vapor HF etching to fabricate freestanding gratings. CAT gratings features lower mass and more relaxed flatness and alignment requirements as compared to conventional reflection gratings while providing high diffraction efficiency to meet the science requirements for potential NASA missions (i.e., Arcus, Lynx).

For the last decade, the technology stood at the stage of developing lab-scale manufacturing process and X-ray demonstration of the CAT gratings. However, as CAT gratings have been selected for potential NASA missions in recent years, understanding the mechanical behavior of the gratings has become an issue as more than one thousand gratings have to be manufactured and assembled in a rapid and reliable way to build a high-resolution scientific instrument with large effective area.

In this work, we present data on imperfections we have observed (1) the buckling of thin grating membranes, (2) grating line stiction. Residual stresses in thin film layers or thermal perturbations are suspected culprits for those "failure modes." Efforts on analysis of residual stresses in thin film layers in SOI wafers are presented. We also present our preliminary efforts on finite element modeling of the grating structure to study how it behaves when certain types of perturbations (i.e., thermal, material removal) are applied.

Programmable Bioinspired Fiber-based Artificial Muscle

8.07

M. Kanik, S. Örgüç, G. Varnavides, J. Kim, T. Benavides, D. Gonzalez, T. Akintilo, C. C. Tasan, A. P. Chandrakasan, Y. Fink, P. O. Anikeeva

Sponsorship: NSF Center for Materials Science and Engineering, NSF Center for Neurotechnology, Simons Center for The Social Brain

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Actuators, biological devices & systems, BioMEMS, electronic devices, energy, energy harvesting devices & systems, medical devices & systems, MEMS & NEMS, microfluidic devices & systems, molecular & polymeric materials, nanomanufacturing, nanomaterials, nanotechnology, sensors.

Mimicking the structure of the cucumber tendrils, we developed a fiber-based artificial muscle that possesses similar functions observed in biological muscle such as agility and feedback. The artificial muscle devices were produced using a cost-effective thermal draw method in extended (10^3 – 10^4 m) lengths and arbitrary scales in the 5 µm to 5 mm thickness range.

The fiber muscle is a bimorph structure which is made of an elastomer and thermoplastic polymer with low thermal expansion coefficient and high expansions, respectively. The fiber muscle self-assembles in helical shape after stretching and releasing. The size and the number of the coils in the helix can be programmed by the applied strain and strain rate. The fiber muscles can be optically and thermally actuated in ambient temperature (ΔT=10 °C). Fiber muscles demonstrate a very rapid force switch rate of 6.33±0.72 N/s and a power-to-mass ratio of 75–90 Wkg^{-1}. They can be contracted up to 50 % and stretched up to 1300 %. These fiber muscles can lift weights 650 times higher than their own weight. To enable a feedback mechanism, we outfitted the muscle fibers with Ag nanowire meshes.

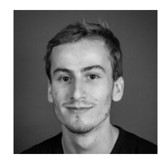
When the fiber muscles were contracted and extended, the change in the length of the fiber was exported as a relative resistance change signal. Inspired by the human arm, we developed an artificial arm that was driven by the artificial muscle fiber. The movement of the arms flowed naturally, similar to human muscle movements. The muscle fibers with arbitrary scalability, high performance, and very low latency can likely find application not only in robotics and prosthetic limb technologies, but also in smart textiles, implantable sensors, and neural engineering.

Modeling Process Uniformity using Gaussian Process Methods

8.08

C. Lang, D. S. Boning

Sponsorship: Applied Materials



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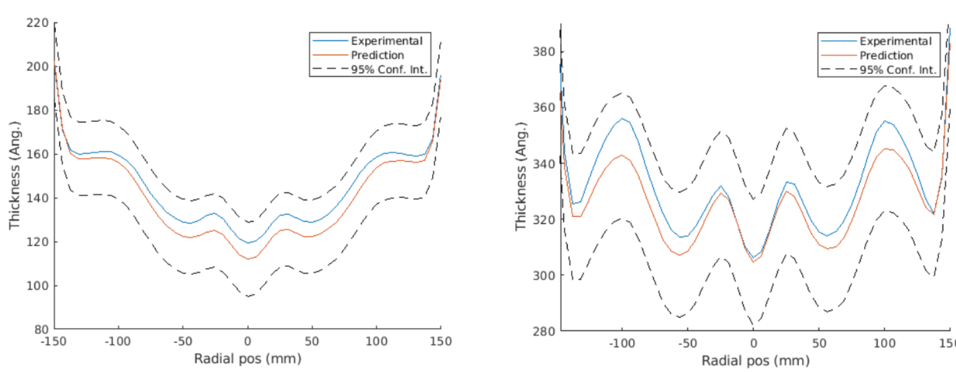
Research Interests:
Electrochemical plating, information processing, machine learning, molecular & polymeric materials, nanomanufacturing, pattern dependent variations, process modeling, spin coating.

Modeling process uniformity is critical for achieving required specifications in many advanced process technologies. For example, sputter deposition systems are prone to significant wafer-scale deposition rate variations due to the complex dynamics of the chamber plasma. Our work focuses on developing and applying machine learning methods for modeling and minimizing these non-uniformities. Traditionally, modeling this process using first physics principles has been particularly difficult due to the chaotic nature of plasma physics. Instead, we model this process using a Gaussian Process (GP) framework. We have successfully modeled the deposition rate across the wafer as a function of both process parameters, such as power and chamber pressure, and as a function of the equipment configuration. Current work is seeking to improve the model accuracy, as well as to develop optimization approaches based on these models.



▲ Model predictions and experimental results for two sets of deposition system parameters. The left shows significant wafer scale thickness variations, while the right shows acceptable variations.

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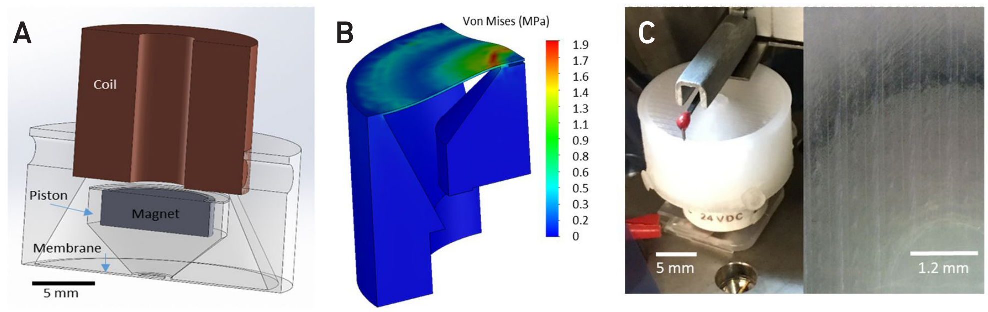
Monolithically 3-D Printed Miniature Magnetic Actuators

8.09

A. P. Taylor, L. F. Velásquez-García

Sponsorship: Edwards Vacuum

Applications of miniature actuators include fluid pumping, where large displacement and force are usually needed to be efficient; however, hardware made via standard microfabrication typically cannot attain such performance. Magnetic actuation is an attractive choice to deliver these requirements in a tiny form factor. We have designed, fabricated, and characterized miniature 3-D printed, monolithic magnetic actuators. The actuator is a frame that holds a coil and a 24 mm dia., 150 µm-thick membrane connected to a piston with a cavity holding an embedded SmCo magnet. The fused filament fabrication method is used to print the actuator body out of Nylon 12. The maximum displacement of a single-layer membrane actuator is equal to 302 µm with 20V DC applied to the coil. Data analysis shows that the magnetic force is proportional to the square of the coil current—as expected from theory. 3-D printing allows for making low-cost actuators with ample performance for integrated fluidic systems.



▲ A: Cross-section of actuator with 3-D printed body, embedded magnet, and coil. B: Finite element result of an actuator's stress field with a 0.12 N force applied. C: A 150 µm-thick membrane actuator while being tested (left) and close-up of the membrane (right).

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Medical devices & systems, MEMS & NEMS, nanomanufacturing, nanomaterials, nanotechnology, sensors, transducers.

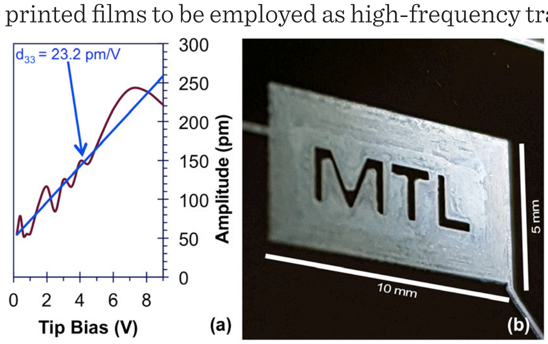
Electrohydrodynamic Deposition of Ultra-thin Zinc Oxide Piezoelectric Films for Printed High-frequency Applications

8.10

B. García-Farrera, D. V. Melo-Máximo, L. F. Velásquez-García

Sponsorship: Monterrey Tec–MIT Nanotechnology Program

Additively manufactured piezoelectric transducers for high-frequency devices are yet to be realized due to the nature of the printable materials. We report the first room-temperature-printed ultrathin ceramic piezoelectric films compatible with high-frequency operation. Homogeneous traces of zinc oxide (ZnO) nanoparticles–as thin as 91 nm–were successfully produced via near-field electrohydrodynamic deposition. Macroscale level piezoelectric behavior was achieved using a novel orientation mechanism based on rastering of the printing nozzle, resulting in imprints with a significant portion of the polar axis in the film plane. Printed film bulk acoustic resonators in lateral excitation achieve resonant frequencies as high as 9.84 GHz, the measured acoustic speed is comparable to that of bulk material, and the average piezoelectric response is significantly higher than that of single-crystal ZnO; proving the suitability of the printed films to be employed as high-frequency transducers.



▲ a) Example of the piezoelectric response due to the electric field in the same direction, the value is larger than that for single crystal zinc oxide. b) MTL logo printed through direct write using zinc oxide nanoparticles.

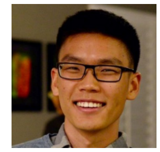
Tunable n-Type Doping of Carbon Nanotubes through Engineered Atomic Layer Deposition HfO_x Films

8.11

C. Lau, T. Srimani, M. D. Bishop, G. Hills, M. M. Shulaker
Sponsorship: Analog Devices Inc., NSF, DARPA

While digital systems fabricated from carbon nanotube-based field-effect transistors (CNFETs) promise significant energy efficiency benefits, realizing these benefits requires a complementary CNFET technology, i.e., CNFET CMOS, comprised of both PMOS and NMOS CNFETs. This CNFET CMOS process must be robust (e.g., air-stable), tunable (e.g., ability to control CNFET threshold voltages), and silicon CMOS compatible (to integrate within existing manufacturing facilities and process flows). Such a silicon CMOS compatible CNT doping strategy for forming NMOS CNFETs does not exist. Techniques today are either not air-stable (using reactive low work function metals), not solid-state or silicon CMOS compatible (employing soluble molecular dopants in ionic solutions), or have not demonstrated precise control over the amount of doping (for setting threshold voltage: V_T).

We demonstrate an electrostatic doping technique that meets all of these requirements. Our technique leverages atomic-layer deposition (ALD) to encapsulate CNTs with nonstoichiometric oxides. We show that ALD allows for precise control of oxide stoichiometry, which translates to direct control of the amount of CNT doping. We experimentally demonstrate the ability to modulate the strength of the p-type conduction branch by >2,500X (measured as the change in current at fixed bias), realize NMOS CNFETs with n-type conduction ~500X stronger than p-type conduction (also measured by the relative current at fixed biases), and tune V_T over a ~1.5V range. Our technique is also compatible with other doping schemes. We combine electrostatic doping and low work function contact engineering to achieve CNFET CMOS with symmetric NMOS and PMOS (i.e., CNFET ON-current for NMOS and PMOS is within 6% of each other). Thus, this work realizes a solid-state, air stable, very-large-scale integration (VLSI) and silicon CMOS compatible doping strategy, enabling integration of CNFET CMOS within standard fabrication processes today.



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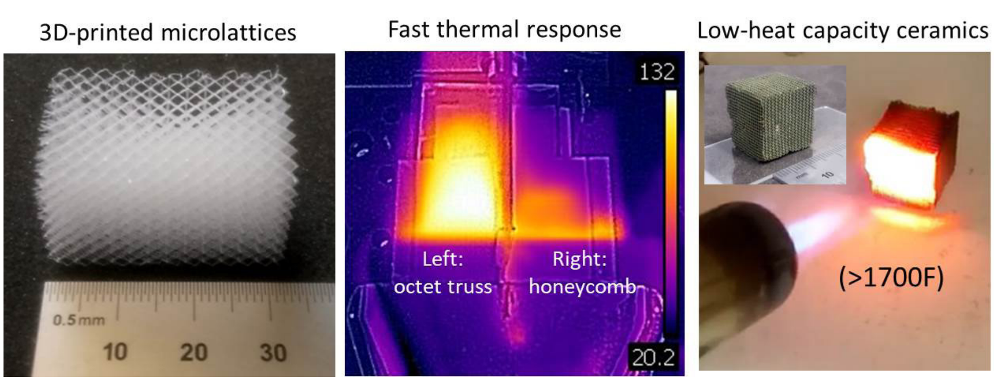
Research Interests:
Electronic devices, electronics, III-Vs, information processing, integrated circuits, nanomanufacturing, nanomaterials, nanotechnology, systems, carbon nanotubes.

3-D Printed Microarchitected Ceramics for Low-heat Capacity Reactors

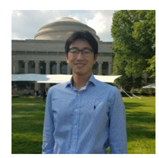
8.12

S. Kim, S. Shin, T. Ganapathy, Y. T. Cho, N. X. Fang
Sponsorship: MIT Energy Initiative

Efficient heat and mass transfer for catalytic reactors are desirable for biological and environmental applications and are of great import to the automotive and power plant industry. Porous substrates with thinner cell/pore walls and higher cell/pore density enable faster catalyst activation due to low-heat capacity, larger surface area, and lower hydrodynamic resistance of working fluids. Manufacturing of well-engineered structures with thin wall and higher cell/pore density remains a challenge. To overcome the limitations associated with the traditional manufacturing process, we study manufacturing-friendly structural design and additive manufacturing processes for microarchitected ceramic substrates with both a high surface area to volume ratio and low-heat capacity. Our central idea for achieving efficient ceramic substrates is to leverage the geometrical benefits of three dimensional (3-D) microlattices of thin-walled hollow-tubes realized through additive manufacturing processes.



▲ 3-D Ceramic catalytic reactor with low-heat capacity and high surface area/volume ratio: example of 3-D printed microlattices; fast thermal response of microlattices; high-temperature resistance of ceramic microlattices.



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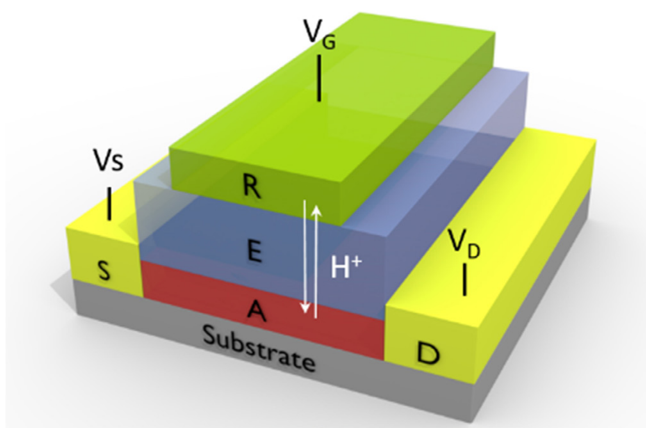
Proton Intercalation Based Resistive Switching for Neuromorphic Computing

8.13

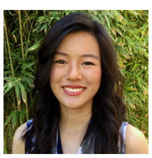
X. Yao, W. Lu, J. A. del Alamo, J. Li, B. Yildiz

Sponsorship: SenseTime, Skoltech

Physical neural networks composed by resistive switching processor arrays can enable in-memory computing with higher operating speed and lower energy cost than the present von Neumann architecture. The state-of-the-art resistive switches rely on the mechanism of either forming conductive filaments or inducing phase change. These mechanisms suffer from poor repeatability or high energy consumption. We demonstrate a three-terminal resistive switching unit with a channel of active material, a proton reservoir and a proton conductive solid electrolyte in between. The conductivity of the active material can be tuned by the exact amount of intercalated protons in it, providing a high reproducibility of the resistive switching behavior. As the lightest cation, the shuffling of protons between layers requires only minimal energy. A proof-of-concept single device has been fabricated. The resistive switching behavior of the device and material property changes of the channel are characterized.



◄ Sketch of the all solid three-terminal "REA" device. "R" is the cation reservoir, "E" is the cation conductor electrolyte, and "A" is the active cation intercalating RS material.



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Research Interests:
Communications, embedded systems, information processing, multimedia, nanotechnology, sensors.

Intelligent Embedded Systems for Complex Equipment Monitoring

8.14

V. Juan, J. Quaye, J. Scholvin

Sponsorship: MIT.nano

Tool interlocks commonly used in shared facilities help enforce logging of tool-use for billing purposes and allow accurate real-time availability indication. The majority of tools at MTL are interlocked, with one interlock per tool, controlled by the CORAL reservation system. These interlocks are networked devices that can switch a DC signal or AC power line to unlock the tool for use. Our project aims at building new types of interlock devices that remain compatible with CORAL. By utilizing the network connectivity and expanding capabilities, we will create a set of smart interlocks that also monitors process- and lab-relevant metrics (e.g., wafer count, material usage, environmental conditions, etc.). Because each interlock is located near its respective tool, we have the opportunity to add new functionality. For example, adding a user interface to display relevant data, manuals, and SOPs, or simplifying the interaction with CORAL for quick and convenient engage/disengage functionalities.

Our poster will show a roadmap of the proposed system architecture, centered around a Raspberry-Pi platform, and how different modular sub-components can be designed and combined in the future, including: (1) tool-interlock functionality compatible with CORAL, (2) real-time and continuous data acquisition, using sensors placed at the tool, (3) local data processing, storage and visualization, (4) paths to import and display lab-wide information acquired by other interlocks or systems (e.g., temperature, humidity, particle count, building vibration), (5) future integration with CORAL APIs, to allow easy and convenient starting and stopping of tool runs, including new paths for user authentication. We will also demonstrate an initial interlock prototype, controlled by CORAL, with a local user interface and data-acquisition as well as data-display capabilities.

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Research Interests:
2-D materials, electronic devices, electronics, energy, nanotechnology, organic materials.

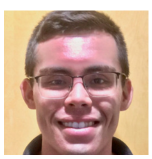
Multi-layer Transition Metal Dichalcogenide Photovoltaics

9.01

E. McVay, A. Zubair, Y. Lin, M. Hempel, T. Palacios
Sponsorship: AFOSR FATE MURI, NASA NSTRF

Single atomic layer transition metal dichalcogenides (TMDs) and their van der Waals heterostructures have been explored extensively for ultrathin optoelectronic applications (i.e., LED, photodetectors, solar cells etc.) due to their direct bandgap and strong light-matter interactions. However, optoelectronic applications of multi-layer TMD thin-films have not been as extensively studied despite their high absorption coefficient (>10^5 cm^{-1}) and wide absorption frequency bandwidth. In this work, we study the electronic transport and photovoltaic characteristics of multilayer WSe_2 devices ranging from ~20nm to ~200nm with the intention that they can later be integrated as part of an energy harvester in a micro-scale sensing system.

We have demonstrated Schottky junction WSe_2 solar cells using dissimilar metal contacts, and investigate the possibilities of using surface doping and electrostatic gating to alter the doping topology within the TMD flake. Notably, the short circuit current of our thin flake devices improves over two-fold when a thin ALD aluminum oxide layer is deposited on top of the device, suggesting that surface effects can drastically limit the performance of thin absorber layer devices. Our highest performing proof-of-concept platinum-WSe_2-gold vertical thick flake device showed an open circuit voltage of 0.34V. Further work is being done to estimate the device efficiency. We further compare the performance of thin film devices and thick film devices and investigate a quasi-lateral topology to improve thin absorber layer device performance. Using this quasi-lateral structure, we demonstrate a device with an open circuit voltage of 0.44V. This project details TMD Schottky diode parameter extraction results, photovoltaic performance measurements, and geometric considerations that can be used as groundwork for further ultrathin solar cell device optimization.



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BioMEMS, electronic devices, microfludic devices & systems.

Lithium Extraction from High Mg^2+:Li+ Brines using Ion Concentration Polarization

9.02

A. Barksdale, J. Yoon, J. Han
Kuwait-MIT Signature Project on Brine Desalination

Over the next decade, electric vehicle ownership will skyrocket with green technology trends against the global climate crisis. The excellent energy density properties of lithium-ion batteries (LIBs) allow for practical driving ranges in consumer electric vehicles (EVs). Growing LIB demand for increasing EV production places strain on LIB electrode material supply, namely battery-grade Li_2CO_3 (>99.5% purity). Future lithium availability must be secured for EV production to tackle the pressing climate issue.

Lithium brine lakes are a promising lithium resource, containing over two-thirds of lithium deposits globally. However, brines contain contaminants like Mg^{2+}, which reduce yield of battery-grade Li_2CO_3 by contaminating intermediates like LiCl (Lithium Carnallite: LiCl $MgCl_2$). Thus, the Mg^{2+}/Li^+ ratio is a critical brine quality metric. Literature suggests a Mg^{2+}/Li^+ of 8 for battery-grade Li_2CO_3 precipitation, while brine ratios can reach 20-80, and even over 1000. Reduction of magnesium in brines is crucial for battery-grade Li_2CO_3 production.

We propose a novel membrane-based method utilizing ion concentration polarization for Mg^{2+}/Li^+ reduction in brines, avoiding chemical additives. In our work, we aim to experimentally verify collaborators' simulation results, achieving a 1:3000 Mg^{2+}/Li^+ flux ratio through device in ideal simulation conditions. We will then build a high-throughput fluidic device by scaling up conditions studied in microfluidic experiments, considering channel dimensions and flow conditions. Demonstration of high throughput, continuous lithium extraction from high Mg^{2+}/Li^+ brines opens doors for realization of plant scale facilities utilizing previously inaccessible high Mg^{2+}/Li^+ brines. This work could assure future lithium availability for EV batteries in face of the climate crisis.

Roll-to-roll Printing of Perovskite Solar Cells

9.03

B. Dou, M. F. A. M. van Hest, V. Bulović

Sponsorship: Solar Energy Research Institute of India and United States, Tata-MIT GridEdge Solar

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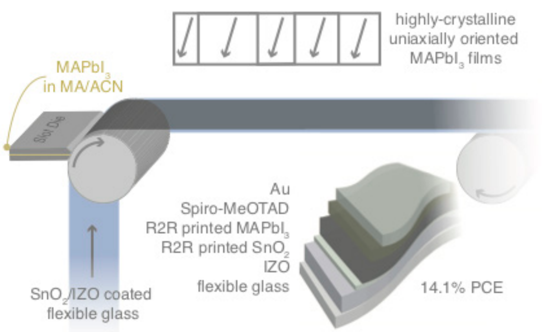
Research Interests:
Energy, nanomanufacturing, nanotechnology, photovoltaics.

High efficiency combined with transformative roll-to-roll (R2R) printability makes metal halide perovskite (MHP)-based solar cells the most promising solar technology. However, translation from lab-scale deposition solution processing techniques to large-scale R2R methods has typically led to reduced photovoltaic performance. In this work, by applying highly concentrated low-boiling point solvents, we demonstrate large-scale, highly crystalline, uniaxially oriented, smooth perovskite films printed at room temperature and in the ambient environment. Confirmed with high-speed synchrotron-based *in situ* X-ray diffraction measurements, the perovskite films reach 98% of relative crystallinity at room temperature and display high texture within 1 s of the coating. With these high-quality MHP films, we demonstrate an all-blade-coated MHP cell with power conversion efficiency (PCE) up to 19.6% (compared to ~18% PCE from non-scalable spin-coating method), a slot-die coated cell with a PCE of 17.3%, and a partially R2R slot-die coated flexible glass-based cell efficiency of 14.1%. This work represents a major advancement toward industrial development of MHP-based solar cells, bringing us one-step closer to the mass production of high-efficiency and low-cost MHP solar cells.



◄ Illustration of R2R slot-die printing setup where $MAPbI_3$ ink is coated on SnO_2/IZO/flexible glass. With Au/Spiro-MeOTAD on the R2R printed $MAPbI_3$/SnO_2/IZO/flexible glass, the solar cell yields up to 14.1% power conversion efficiency.

Graphene Electrodes and Enhanced Zinc Oxide Nanowire Growth for Efficient and Cost-effective Lead Sulfide Quantum Dot Photovoltaics

9.04

M. H. T. Dastjerdi, M. M. Tavakoli, N. Moody, M. Bawendi, J. Kong, S. Gradečak

Sponsorship: Eni S.p.A. under the Eni-MIT Alliance Solar Frontiers Center, NSERC Canada

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Lead sulfide (PbS) quantum dots (QDs) have emerged as promising candidates for photovoltaic (PV) applications due to their facile solution processing, direct bandgap and material stability. Zinc oxide (ZnO) nanowires (NWs) have been incorporated to improve carrier extraction and graphene bottom electrodes have been used toward realization of flexible QD-based PV devices. Since in such device structures ZnO NWs are infiltrated with QDs, it is expected that NW geometry (e.g., density, length, or morphology) affects the carrier extraction and thereby overall device performance. However, the role of the NW geometry relative to the QD properties remains unexplored, in part due to challenges with controlled NW synthesis. Here, we use the precursor concentration as a handle to tailor ZnO NW growth and thereby PV characteristics resulting in power conversion efficiency beyond 10%. Lowering the precursor concentration results in the improvements of fill factor (FF) and open-circuit voltage (Voc) likely due to: a) reduced NW areal density and thus a lower number of surface states, b) improved scattering of the incoming light resulting in increased optical path length and c) enhanced infiltration of NWs with QDs.

Furthermore, we also explore how to develop semi-transparent PbS QD PV devices by adding a graphene top electrode. We achieved the first PbS QD PV device with graphene as top electrode by optimizing the transfer process of graphene sheets grown by chemical vapor deposition. Replacing the currently dominant, but expensive gold top electrode with transparent graphene not only reduces the cost of device fabrication, but also allows for illumination of the device through the top electrode. Our results show that this leads to increased density of photo-generated carriers, evidenced by a >10% increase in short-circuit current density.

In conclusion, we show improved PbS QD PV device performance through optimization of ZnO NW growth. Also, we demonstrate the first semi-transparent PbS QD PV device with a graphene anode electrode. Our results pave the way for efficient and cost-effective processing for large scale and high throughput QD PV device fabrication.

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Crystal Engineering of Mixed Cation Perovskite for Fabrication of Highly Efficient Solar Cell

9.05

M. M. Tavakoli, J. Kong

Sponsorship: ENI S.p.A under the MITEI Solar Frontier Center

Inorganic-organic perovskite solar cells (PSCs) have caught tremendous interest of many research groups in the field of photovoltaic devices due to their low-cost, ease of fabrication and, excellent optical and electrical properties, which resulted in a record certified PCE of 23.3%. The presence of surface and grain boundary defects in organic–inorganic halide perovskite films is detrimental to both the performance and operational stability of PSCs. Here, we study the effect of chloride (Cl) additives on the bulk and surface defects of mixed-cation and halide PSCs. We found that using an anti-solvent technique, the perovskite film is divided into two separate layers, i.e., the bottom layer with large grains and a thin capping layer with small grains. Moreover, we demonstrate that the addition of formamidinium chloride (FACl) into the precursor solution removed the small grain perovskite capping layer and suppressed the formation of bulk and surface defect. This provides the perovskite film with remarkably increased orientation, crystallinity, and large grain size up to over 1 μm. Time-resolved photoluminescence measurements show longer lifetimes for perovskite films modified by FACl and subsequently passivated by 1-Adamantylamine hydrochloride (ADAHCl) as compared to the reference sample. Based on these treatments, we improve the quality of perovskite film and increase the power conversion efficiency (PCE) from 19.43% for reference sample to 21.2% for modified device by Cl additives. This efficiency is among the highest reported value for planar perovskite solar cell. This PCE enhancement is mostly due to the improvement of open circuit voltage (V_{oc}) from 1110 mV to 1152 mV. Moreover, the modified device by Cl additives shows lower hysteresis effect as compared to the reference. Importantly, the molecular engineering of applying Cl additives greatly enhances the stability of the PSCs, which show only 5% degradation after aging for 90 days which is higher than the reference device with 16% PCE loss. Additionally, we found that the modified device with Cl additives shows better ideality factor of 1.8 compared to 2.1 for the reference, due to the lower recombination. Our proposed approach opens up a new direction for commercialization of efficient and stable solar cell devices.

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Research Interests:
Energy, photovoltaics.

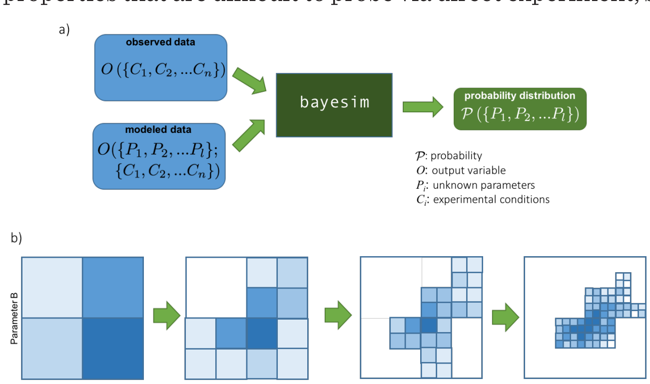
Semiconductor Parameter Extraction from Photovoltaic Device Measurements via Bayesian Inference

9.06

R. C. Kurchin, J. Poindexter, G. Romano, T. Buonassisi

Sponsorship: Blue Waters Graduate Fellowship, Center for Next-Generation Materials by Design (an NSF EFRC)

Bayesian parameter estimation is a common approach for model optimization in fields including astrophysics, high-energy physics, and bioinformatics. However, it has not been adopted extensively for electronic device characterization. We developed an open-source Python code, Bayesim, that accepts sets of observed data as a function of experimental conditions and modeled data as a function of those same conditions as well as a set of parameters to be fit, and outputs a probability distribution over these parameters, accounting for both experimental and model uncertainty. Because models of electronic devices can be computationally expensive, we adopt an adaptive grid scheme for sampling the parameter space. The code has proven successful in fundamental characterization of photovoltaic materials using experimental measurements on finished devices and represents a new method for measurement of properties that are difficult to probe via direct experiment, such as defect parameters.



◄ a) high-level flowchart illustrating the function of Bayesim. b) Schematic illustrating the adaptive grid refinement of the parameter space. Darker colors indicate higher probabilities; only higher-probability regions are subdivided.

Bubble Engineering during Electrochemical Reduction of CO_2

9.07

S. Khan, J. Hwang, Y. Shao-Horn, K. K. Varanasi

Sponsorship: ENI

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Research Interests:
Batteries, energy, energy harvesting devices & systems, nanomanufacturing, nanomaterials.

Over the past several years, the concentration of CO_2 in the Earth's atmosphere has risen at an alarming rate, resulting in an increase in global temperatures. Electrochemical reduction of CO_2 has been studied for many years as a promising approach towards reducing atmospheric CO_2 levels and converting CO_2 to usable fuels. While most research in this field continues to focus on developing new catalysts for reduction, very few studies have characterized CO_2 depletion during the electrochemical process especially near the catalyst surface, in addition to efficient ways of replenishing CO_2 consumed during the reaction. A major challenge remains in minimizing co-evolution of hydrogen as well as maintaining a sufficiently high CO_2 concentration in the electrolyte.

Herein we report the effect of trapping CO_2 bubbles on superhydrophobic surfaces in close proximity of the catalyst on the corresponding current density (a measure of the reaction rate) and gaseous product distribution mix during CO_2 reduction. When a single CO_2 bubble is trapped near the catalyst, methane selectivity is improved, and hydrogen co-evolution is suppressed owing to increased availability of locally dissolved CO_2 in the proximity of the catalyst thereby favoring increased production of hydrocarbon products.

We also demonstrate a scalable process whereby flowing a continuous stream of CO_2 bubbles directly on the superhydrophobic trap in close proximity to the catalyst provides numerous advantages overs bubbling CO_2 at the same flow rate in the bulk electrolyte. The current density associated with the reduction when bubbled on a superhydrophobic trap is improved by as much as 25% compared to regular bubbling in the bulk. This research shows an excellent path forward towards commercialization in the field of electrochemical reduction of CO_2 where no scalable process presently exists.

Lateral Multijunction Photovoltaics on Ge-on-Si Virtual Substrate

9.08

R. Wen, D. Li, J. Michel

Sponsorship: ARPA-E

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Research Interests:
Photovoltaics, III-V materials.

Lateral multijunction photovoltaics based on III-V direct bandgap semiconductors enable efficient energy conversion. However, lattice matching between cell and substrate requires the use of expensive Ge or III-V substrates, which limits widespread application of III-V solar cells. Cost reduction can be achieved by using Ge-on-Si virtual substrate where a thin layer of Ge is grown on relatively inexpensive Si substrates, thanks to the greater material abundance and larger wafer diameters of Si. However, the lattice mismatch between Si and Ge can bring about threading dislocations that can significantly impair efficiency of solar cells.

We show that patterned growth of pure Ge on Si through ultrahigh vacuum chemical vapor deposition can achieve sufficiently low threading dislocation density by localizing dislocations while leaving the rest of the patterned area defect free. This unlocks the potential for growing lattice-matched III-V photovoltaics of high-quality on top of the virtual substrate.

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Research Interests:
Electronic devices, electronics, energy, energy harvesting devices & systems, integrated circuits, medical devices & systems, MEMS & NEMS.

A Silicon MEMS EM Vibration Energy Harvester

9.09

Y. Yang, U. Radhakrishna, D. Ward, A. P. Chandrakasan, J. H. Lang
Sponsorship: Analog Devices Inc.

With the advent of machine health monitoring, the concern of finding an efficient method to power machine health sensors naturally arises. Keeping the sensor and an energy harvester in the same compact package provides install-and-forget sensor systems that are self-reliant and introduces no extra maintenance concerns. For industrial machineries, an electromechanical MEMS based-transducer can provide an efficient interface between industrial machines and the rest of the vibration-based energy harvesting system.

In this work, an optimized silicon-MEMS electromagnetic vibration energy harvester suitable for such applications is developed. The harvester comprises a deep reactive-ion etched silicon suspension, and pick-and-place NdBFe magnets and copper coils, all in a 3D printed package. Mechanical and magnetic optimization yielded a design with an active volume of 1.79 cm^3, and an output power P_{Out} of 2.2 mW at 1.1 g and 76 Hz under matched load. This corresponds to a power density of 1.23 mW/cm^3 and a normalized power density of 1.02 $mW/cm^3/g^2$, the highest among silicon-based MEMS harvesters reported to date. The four bar-linkage suspension lowers beam stress compared to our earlier accordion suspension, enabling mm-range strokes and hence mW-level P_{Out}. The key contributions here are: (i) large-stroke (2 mm) silicon suspensions with stress analysis, (ii) harvester implementation yielding P_{Out} = 2.2 mW, and (iii) optimized design guidelines to reduce harvester size while preserving P_{Out}. These improvements yield an energy harvester capable of powering machine health sensors.

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Silicon Hybrid Micro Rocket Engine using Steam Injector and Peroxide Decomposition

9.10

J. M. Protz
Sponsorship: microEngine, LLC; Asteria Propulsion, LLC.

Rocket engines miniaturized and fabricated using silicon MEMS have been an active area of research for two decades. At these scales, miniaturized steam injectors like those used in Victorian-era steam locomotives are viable as a pumping mechanism and offer an alternative to pressure-feed and high-speed turbo-pumps. Previously, we demonstrated the feasibility of this pumping concept by designing and testing two ultra-miniature-machined stainless steel micro jet injectors (10 and 100 µm throats) that pumped ethanol and by exploring liquid bi-propellant engine designs. Current efforts are focused on designing a test article and fabrication process that integrates a jet injector, a decomposition chamber, and a thrust chamber with a solid SU-8 fuel grain to form an injector-pumped MEMS hybrid micro rocket.

Session 10: Medical Devices and Biotechnology

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Research Interests:
Biological devices & systems, computer vision, medical devices & systems, multimedia, signal processing.

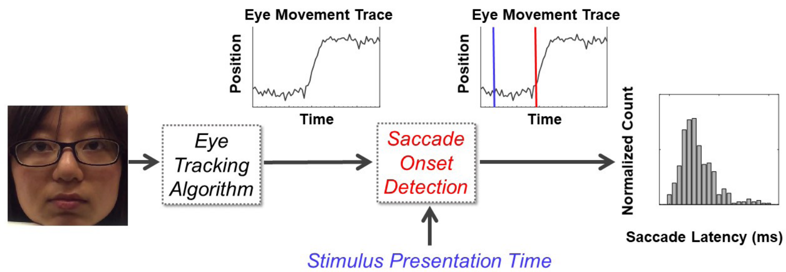
Measuring Saccade Latency using Consumer-grade Cameras

10.01

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

Sponsorship: SenseTime

With current clinical techniques, it is difficult to accurately determine the condition of a patient with a neurodegenerative disease (e.g., Alzheimer's Disease). The most widely used metrics are qualitative and variable, exposing the need for a quantitative, accurate, and non-obtrusive metric to track disease progression. Clinical studies have shown that saccade latency - an eye movement measure of reaction time - can be significantly different between healthy subjects and patients. We propose a novel system that measures saccade latency outside of the clinical environment using videos recorded with a consumer-grade camera. This is challenging, given the absence of infrared illumination and high-speed cameras, adverse lighting conditions, and the instability of the tracking device. With our system, we recorded over 20,000 latencies in 30 subjects and showed that individualized, unobtrusive tracking of neurodegenerative disease progression is a possibility.



▲ Saccade latency measurement system, which processes a video recording and outputs a set of saccade latencies. Saccade latency is the time difference between the blue and red lines.

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Research Interests:
2D materials, biological devices & systems, BioMEMS, integrated circuits, medical devices & systems, MEMS & NEMS, microfluidic devices & systems, nanomanufacturing, optoelectronics, photonics, sensors, Si, systems.

CMOS Nanofluidic Chip for Molecular Separation and Sensing

10.02

J. Kim, R. J. Ram

Sponsorship: Bose Foundation and Kwanjeong Educational Foundation

Measurement of protein concentrations are not only useful in a clinical setting but are also useful in the context of monitoring the potency of cell therapy products. Lab-on-CMOS is an attractive platform for addressing this problem because it can integrate complex fluidics with sensing elements on a single chip. Our group has previously demonstrated the fabrication of sub-100 nm tall fluidic channels on a CMOS chip. This poster presents work in progress to design sensors using this CMOS nanofluidic platform. Comsol simulation package was utilized to explore two label-free methods of protein sensing: capacitive and resistive. Electrode geometry and material characteristics were based upon a fabricated CMOS device. Simulation results indicate that resistive sensing is more sensitive compared to the capacitive modality. Side-to-side comparison of capacitive and resistive sensing with the same electrode geometry along with some promising resistive sensing strategies will be presented.

Focal Manipulation of Neural Interstitial Ion Concentration using Ion-Selective Membrane Electrodes

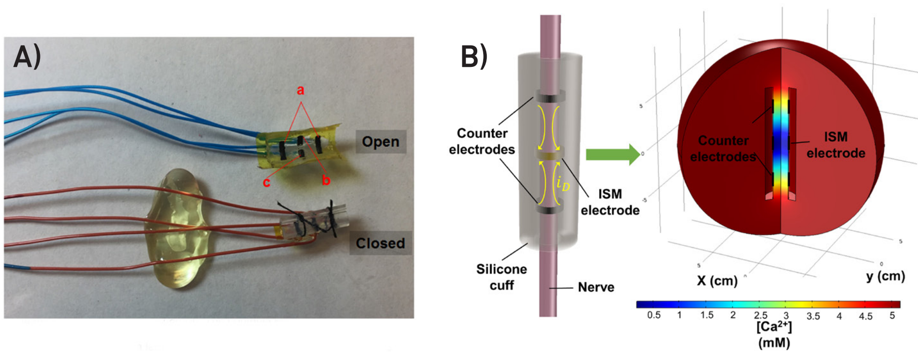
10.03

M. T. Flavin, D. K. Freeman, J. Han

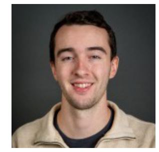
Sponsorship: Draper Laboratory

Neurological diseases, such as chronic pain, have long resisted chemical intervention strategies. Impeded by transport barriers, such as the blood-brain barrier, pharmaceutical agents rarely reach their intended target through systemic administration. Confronting these limitations, our research group has developed a strategy based on an implantable electronic prosthetic device. This device, comprised of an ion-selective membrane (ISM) coated electrode, affects focal changes in chemical concentration under the control of an electrical current.

Here, we report preliminary outcomes from in vivo modulation of interstitial Ca^{2+} concentration via an ISM-based device surgically implanted on the rat sciatic nerve (see Figures 1A and 1B). Consistent with mathematical modeling and previous in vitro results, Ca^{2+} depletion reduces excitation thresholds. Ultimately, we endeavor to demonstrate the ability of Ca^{2+} modulation in peripheral nerve targets to treat chronic pain.



▲ ISM-coated cuff electrode. A) Image of prototype device. B) Schematic and simulation results for mathematical model of chemical modulation in ISM cuff electrode system.



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Research Interests:
Biological devices & systems, BioMEMS, microfluidic devices & systems.

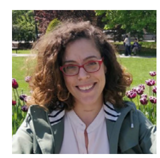
Towards Raman Spectroscopy for Blood Assays and Cell Therapy Monitoring

10.04

N. Persits, R. J. Ram

Raman spectroscopy is a useful tool for characterization of biological and chemical compounds and is used extensively for material detection. In recent years Raman spectroscopy has also been recognized as a potential medical diagnostics tool, enabling quick and chemical-free detection of many analytes such as proteins, glucose, triglycerides and many more. Previous work had demonstrated detection of analytes in clear aqueous solutions but detection in the complex environments of human serum or blood remains challenging due to intrinsic inhomogeneity, scattering, and sensitivity limitations.

This work presents the ongoing research carried out in our group towards the qualitative measurement of analytes in human serum focusing on enhancing the sensitivity and repeatability which are paramount for clinical use. In addition, we introduce a road-map towards the use of Raman spectroscopy as a means to monitor and assess in real time the potency of cell therapies during development and manufacturing. This research has the potential to reduce the number and cost of standard serum tests as well as significantly enhance the yield of cell therapies, making them more effective and affordable.



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All-Solid-State Glucose Fuel Cell for Energy Harvesting in the Human Body

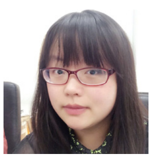
10.05

P. Simons, M. A. Gysel, J. L. M. Rupp
Sponsorship: Merck KGaA, Darmstadt, Germany; Broshy Graduate Fellowship

Efficiently powering sensors, pacemakers and bio-electronic devices for the human body defines a new era of medicine to track, support and operate body functions. Glucose fuel cells have seen a renaissance in recent years as an implantable power source harvesting energy from readily available fuels in the human body. Compared to existing implantable batteries, glucose fuel cells do not require frequent replacement surgery. However, state-of-the-art glucose fuel cells are primarily based on polymer electrolytes being relatively bulky, suffer from long-term stability issues and exhibit low power densities.

Here, we innovate a miniaturized glucose fuel cell, which is fully composed of solid state materials based on thin film processing. This all-solid-state glucose fuel cell can be scaled down to the sub-micrometer range for unprecedented miniaturization and is built on a Si-chip using semiconductor fabrication methods suitable for integrated and direct powering of bio-electronic implants. Free-standing fuel cell membranes based on a proton conducting oxide on Si-chips were assembled using a microfabrication route with standard semiconductor processing techniques. In this presentation, we will show that the proposed cell is electrochemically active and shows promise in functioning as the first all-solid-state glucose fuel cell with a roughly 100-fold lowered thickness of the device (only 250 nm) compared to polymer-based glucose fuel cells.

First IV-curve measurements show a maximum power density of 1.4 μW cm^{-2} and a peak open circuit voltage of 857 mW. These performance values are already comparable to state-of-the-art research-stage glucose fuel cells, even prior to any further engineering of the rate-limiting step. This indicates that through the use of abiotic catalysts instead of conventional biological catalysts such as enzymes and microbes and through an unprecedented degree of miniaturization, long term stability and increased power density are in perspective.



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Research Interests:
Biological devices & systems, nanomaterials, nanotechnology.

Chemomagnetic Modulation of Targeted Neural Circuits

10.06

S. Rao, R. Chen, A. LaRocca, M. Christiansen, A. Senko, C. Shi, P. Chiang, G. Varnavides, J. Xue, Y. Zhou, S. Park, R. Ding, J. Moon, G. Feng, P. O. Anikeeva
Sponsorship: Simons Foundation to the Simons Center for the Social Brain at MIT, DARPA, Bose Research Grant, NIH BRAIN Initiative

Connecting neural circuit output to behavior can be facilitated by precise chemical manipulation of specific cell populations. Local delivery of neuromodulators within the brain allows linking of their molecular targets to behavior. The engineered receptors exclusively activated by designer small molecules enabled manipulation of specific neural pathways. Their application to studies of behavior has so far been limited by the low temporal resolution and the need for invasive implanted cannulas or infusion pumps.

Here, we developed a remotely controlled chemomagnetic modulation – a technique to pharmacologically modulate targeted neural population with temporal and spatial precision in freely moving mice. The heat dissipated by magnetic nanoparticles in the presence of alternating magnetic fields triggered small molecule release from thermally sensitive lipid vesicles with 20 s latency. Coupled with chemogenetic activation of engineered receptors, this technique permitted control of the activity of specific neurons. Delivery of chemomagnetic particles to the ventral tegmental area allowed remote temporally precise modulation of motivated behavior in mice.

Furthermore, the chemomagnetic approach could activate endogenous circuits by enabling regulated release of receptor ligands. Applied to a dopamine receptor D1 agonist in the nucleus accumbens, chemomagnetic modulation increased sociability in wild type mice. By offering temporally precise control of specified ligand-receptor interactions in neurons, this approach may facilitate molecular neuroscience studies in behaving organisms.

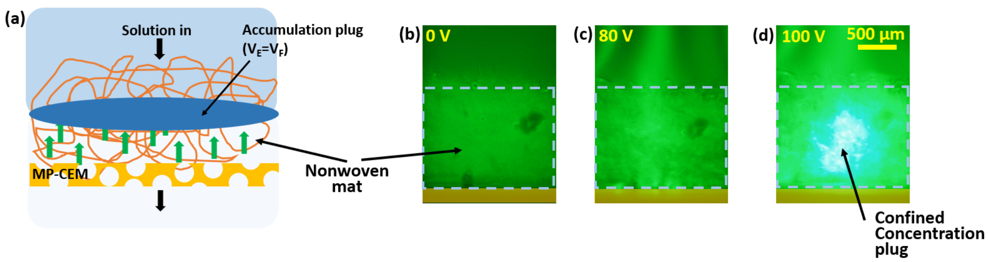
Fast and High-throughput Bio-molecule Concentrator Based on Electrokinetics

10.07

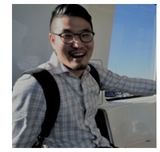
H. J. Kwon, K. Choi, J. Han

Sponsorship: NIH R01

There is a large unmet need for technologies that can provide quick and sensitive detection of waterborne pathogens for human health. To do that, very low concentration of virus should be detected. For example, only 10 noroviruses can infect humans, therefore, 100~200L of water should be concentrated to detect the virus. So far, sub-nano filter, which has a large surface area due to its inherent problem, which are substantial pressure drop and low flow rate, is used for concentration, and this is a bottleneck. We propose to adopt electrokinetic force instead of sieving by pore that can concentrate charged bio-molecules in fast and high-throughput. This device is based on unique membrane, termed MP-CEM (Multi-Pore Cation Exchange Membrane). This MP-CEM has hierarchical pores, which are nano and micro-sized. Using the prototype that can support 2.5ml/min, we have demonstrated the concentration of up to +99 % bacteria using the MP-CEM contained in the ~55mL original volume, in ~20mins.



▲ Micro-sized pore allows fast passage of fluid (water) by hydraulic pressure while nano-sized pore allows ionic flow (cation) by electric field inducing strong electrokinetic force to block all charged molecule (accumulation plug).



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Research Interests:
Biological devices & systems, BioMEMS, MEMS & NEMS, nanomanufacturing, nanomaterials, nanotechnology.

Large-scale Brain Recording with Single Neuron Precision

10.08

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Sponsorship: Fannie and John Hertz Foundation (SR, AM, MM), NIH Director's Pioneer Award (ESB), NIH grants (ESB, AM)

Understanding the brain is a major scientific challenge, and the ability to record the activity of neurons at a large scale can provide important insights into the brain function. The electrode is a classic neural recording technology which can not only provide single neuron resolution but also has the ability to measure endogenous electrical signals in the brain without the need for exogenous contrast agents (such as genetically encoded fluorescent proteins which are required in optical recording technology). However, electrodes have limitations in scaling to the simultaneous observation of large numbers of neurons. Electrode-based recording systems typically require a separate electrical connection/wire for every recording site. Therefore, with the increase in the number of neurons to be recorded (and thus, increase in recording sites required), the number of wires that needs to be routed out of the brain also increases. Creating such complex electrical wiring becomes prohibitively challenging for long probe lengths, e.g., with lengths of centimeters, which is required for recording deep into the brain tissue.

To overcome these challenges, we designed a fiber optic-based recording technology, where a single optical fiber can act as distributed sensors through the principle of fiber optic reflectometry. The sensors transduce the endogenous neural electrical signals into changes in refractive index in the fiber, thus, modulating the optical reflections, which can be detected by an external acquisition system. This technology, if physically realized, would provide the ability to read out neural activity over several centimeters offering access to deep brain regions, would allow miniaturization of the physical dimensions of the fiber without sacrificing performance, thus, minimizing invasiveness and would enable multiplexing of tens of thousands of recordings into a single fiber, creating the possibility for large scale brain recording with single neuron precision.

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Research Interests:
2D materials, Biological devices & systems, electronic devices, electronics, energy harvesting devices & systems, integrated circuits, medical devices & systems, molecular & polymeric materials, nanomanufacturing, nanomaterials, nanotechnology, quantum devices, sensors, transducers.

Small-diameter Endoscope Capable of Visualization and Laser Therapy through a Common Optical Aperture

10.09

M. R. Johnson, A. Zeidan

Sponsorship: Canon

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Research Interests:
Biological devices & systems, electronic devices, electronics, lasers, medical devices & systems

Minimally invasive surgical (MIS) techniques have been widely adopted over recent decades because they require smaller incisions, result in less damage to nerves, tissues, and bony structures, and often cost less than traditional open surgical procedures. One of the enabling instruments for minimally invasive surgery is the endoscope, which allows the surgeon to visualize and often execute surgical action on the target tissue through a small incision or natively existing opening in the body. A fiber-coupled laser is commonly employed as the surgical tool of choice.

The diameter of the endoscope and its ability to deploy a fiber-coupled laser are key instrument parameters and limit which conditions can be treated via MIS. Current endoscope technology uses distinct optical apertures for visualization (CMOS sensor or bundled fibers) and laser delivery, resulting in a device diameter limited by the sum of the two aperture diameters. Spectrally Encoded Endoscopy (SEE) uses a flexible fiber-optic based optical chain with a diffraction grating as the final element to spatially distribute a (broadband) optical signal across a given scene. When the device is azimuthally rotated while collecting the optical return signal, a high-quality image can be reconstructed.

The objective of this work is to add the capability of delivering therapeutic laser energy through the same SEE aperture as is used for visualization, resulting in a very small diameter surgical device capable of both visualization and laser-light therapy. The design and capabilities of a prototype will be presented. As a result of the instrument's reduced diameter, the reach of MIS techniques may be expanded to anatomies previously disqualified due to their small diameter.

Biochip for Drug Delivery using TERCOM

10.10

J. M. Protz

Sponsorship: BioMolecular Nanodevices LLC, LMAG LLC.

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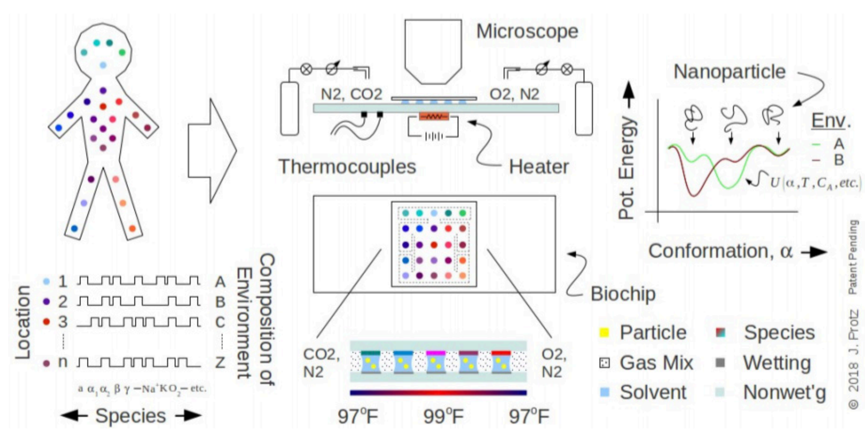
Professor at Duke University

Targeted drug delivery is an area of active investigation and has been for several decades. Most approaches target cell-borne receptors chemically or via genetics. Some use external stimuli such as heat or radio waves to drive spatially-localized release. In one approach, particles estimate their own location within the body by correlating their sensed fluid environment (e.g., temperature, pressure, salinity, sugar levels, pH, etc.) against a carried map and release a charge of drug on the basis of this estimate; this eliminates external aids and is closely related to terrain contour matching (TERCOM), a technique used in aircraft navigation. Previous work by the PI and his group focused on the development of nanoparticles capable of sensing and retaining memory of their environment. Present efforts focus on the theory of estimating location within the body from vectors of sensed variables and on development of a SiO_2 MEMS biochip (micro array) that can test or screen particles and molecules for such sensitivity.



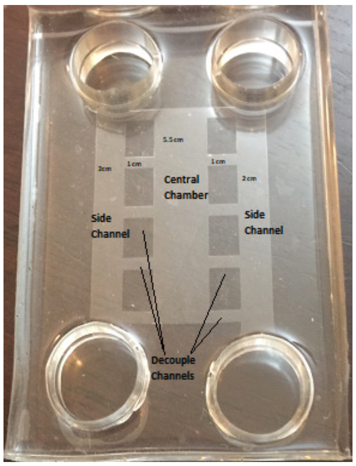
▲ Illustration of biochip screening for TERCOM-functional nanoparticles.

A Simplified Design for Modeling Coronary Capillary Fluid Transport in a PDMS Model

10.11

N. Assefa, S. Poesse

Myocardial injury is the leading cause of adult mortality in the United States. Despite the tremendous scientific interest in modeling the cardiac capillary damage that is characteristic of this event, there are few platforms to accurately model in vivo fluid dynamics, especially capillary interactions. Tissue interfaces mimicking microfluidic devices are the few in vitro models for studying the critical behavior of capillaries, but frequently-used models require single micrometer resolution photolithography tools. This study examines and evaluates an accessible alternative design that employs centimeter resolution photolithography to achieve similar flow properties. Although fundamental fluid dynamic properties of the new design are in accordance with expectations, some suggestions are made to improve the applicability of the new design for modeling cross-membrane diffusion in capillaries.



◄ Current design.

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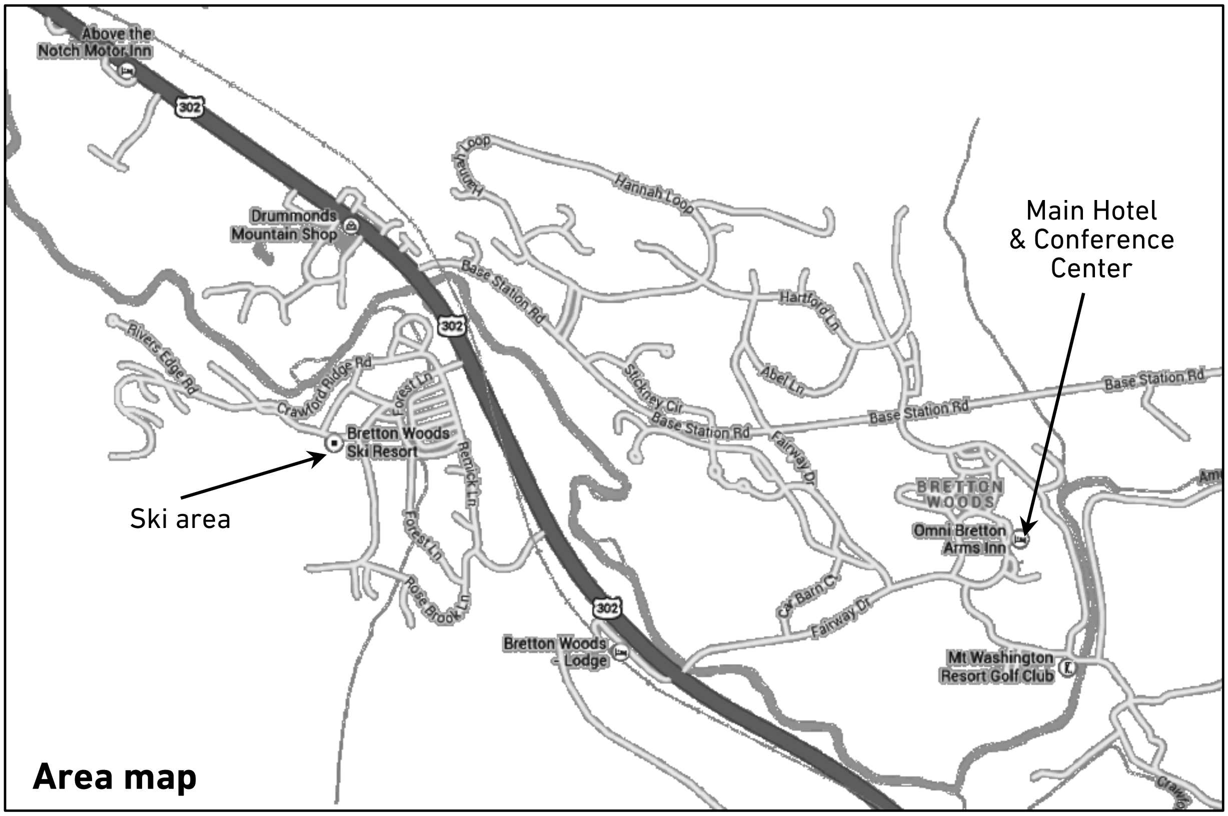
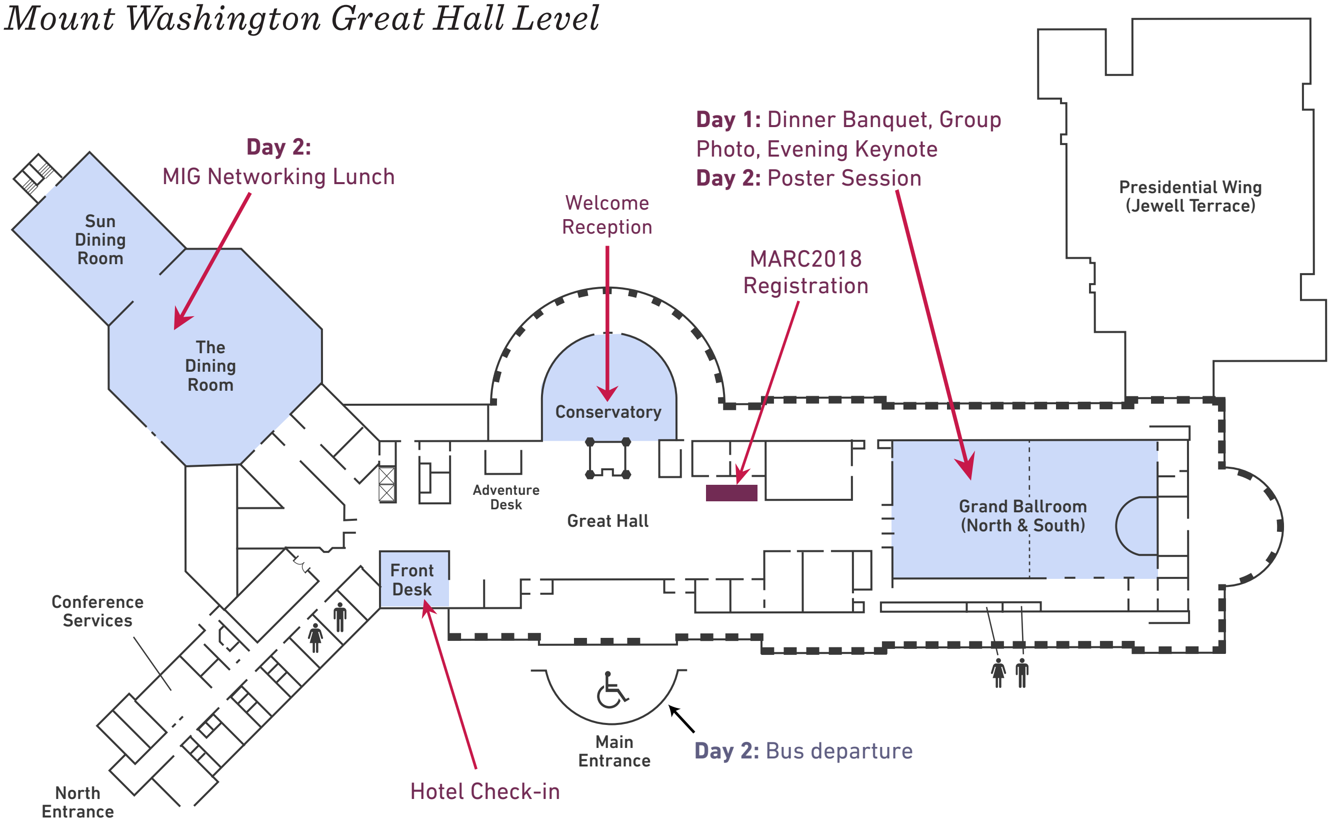
Research Interests:
Biological devices & systems, BioMEMS, microfluidic devices and systems.

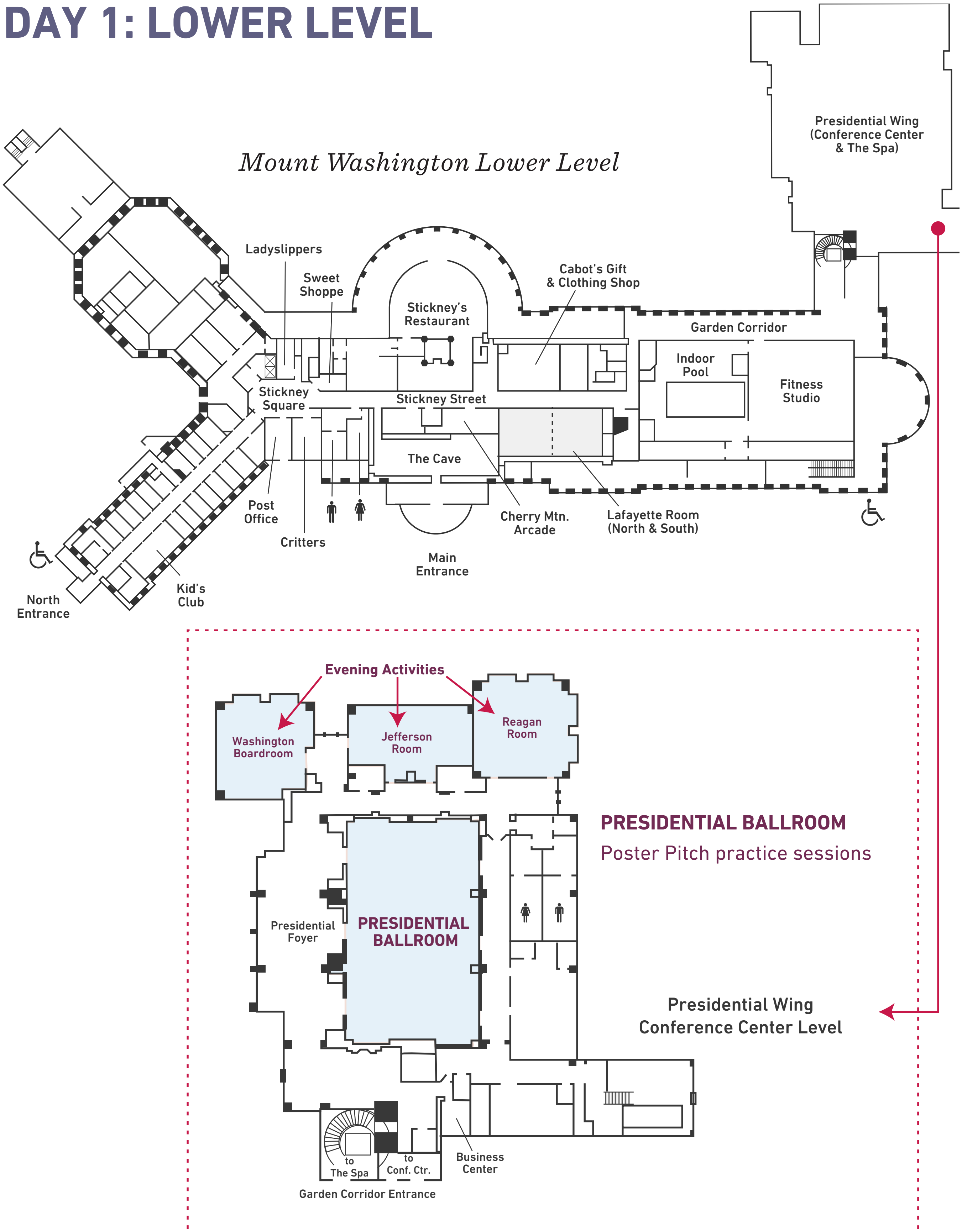
MAPS



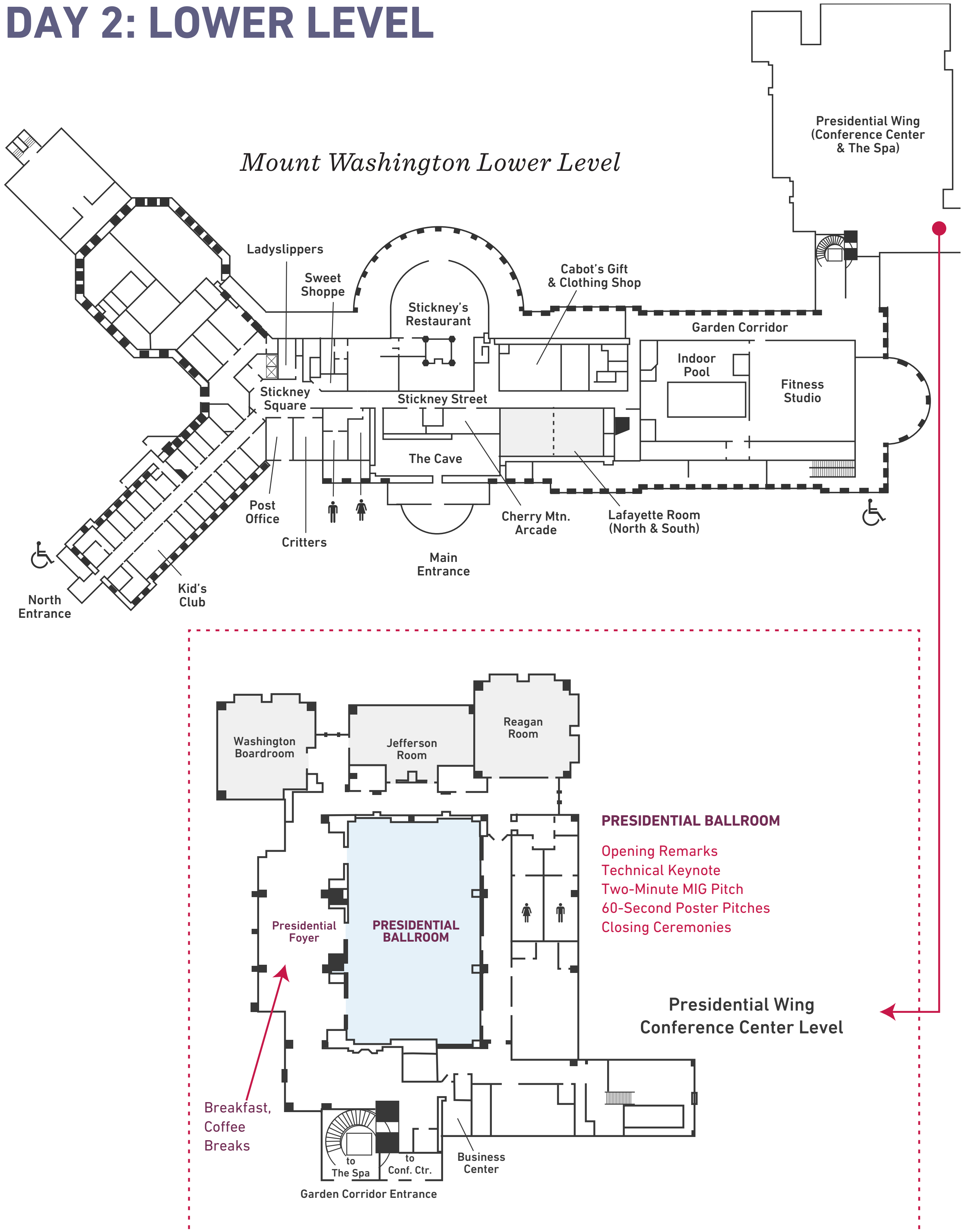
Mount Washington Great Hall Level



DAY 1: LOWER LEVEL



DAY 2: LOWER LEVEL



MAKING A MARC ON HISTORY

MARC has evolved tremendously over time. It had evolved so much that it confuses others on when and how it actually began. Let's take a walk through the history of MARC together and learn some fun facts along the way.

MARC was not always called MARC. With its inception in 1984, MTL became a part of the semesterly VLSI Research Reviews under the Microsystems Research Center. These reviews evolved under the guidance of Prof. Paul Penfield to the faculty-run annual Microsystems Research Review in 1990, later referred to as MTL Annual Student Reviews. The yearly gathering became a student-run conference in 2005 and was rebranded to MARC by Prof. Anantha Chandrakasan. The name has proudly stuck since.

In the past few decades, the MTL research gatherings have been held at several local and far away venues including the Endicott House, the Academy of Arts and Science, MIT campus, Waterville Valley, Marriott Cambridge, Marriott Quincy, and others. Skiing, one of the great offerings of MARC 2019, first premiered at Waterville Valley, NH, over a decade ago. However, the inclusion of winter sports came at a price. In 2009, a winter storm required a last-minute venue change from New Hampshire back to the MIT campus with only hours to spare before the conference -- a Herculean challenge that the organizers met, but with some stress. Lessons learned, the conference took place locally for a few years until being lured back to the mountains in 2014, finding its current home in Bretton Woods. The Omni Mount Washington Resort turns out to be quite a crowd-favorite, and we return to this historic venue for the fourth time in the last five years!

MARC continues to build on the success of past conferences and the vision of former co-chairs and steering committees, combined with a new lens every year. The tradition of publishing proceedings with a digest of abstracts started in 2005 and had been carried forward since. MARC 2010 introduced "Poster Hunt" to engage the attendees more during the poster sessions, another trend which has sustained. By 2012, the registration and abstract submission went from email-based to being fully centralized through the website, which (we hope you agree) improves every year. MARC 2016 introduced the popular Escape the Lab game, and 2017 saw the advent of 2-minute MIG member pitches. MARC 2018 offered poster/pitch workshops to the authors as well as night-before practice sessions. This year continues these successful trends and advances them with longer poster sessions, an interactive Q&A with the evening speaker, more options for social/winter activities, and other behind-the-scene upgrades.

We hope you enjoyed this little ride through history. Here's to many more years of MARC!

AUTHOR INDEX

MTL : MICROSYSTEMS TECHNOLOGY LABORATORIES

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