MARC 2018

MICROSYSTEMS ANNUAL RESEARCH CONFERENCE

JANUARY 29–30, 2018 • BRETTON WOODS, NH

Massachusetts Institute of Technology

MTL MICROSYSTEMS TECHNOLOGY LABORATORIES

MTL EXPO 2018

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First printing, January 2018
PDF version 1.0, January 2018

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INTRODUCTION

Dear colleagues,

Welcome to MARC2018, the 2018 Microsystems Annual Research Conference! This conference brings together the research community and industrial partners of the Microsystems Technology Laboratories (MTL) to celebrate the latest research achievements and explore opportunities for future collaborations. 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: in the heart of MIT campus, the new MIT.nano building awaits its final touches. What has stayed constant through the decades is MTL's dedication to celebrating research and fostering the MTL community. This year, we take a shallow dive into the history of MARC in the section "Making a MARC on History".

MARC2018 features the work of 43 research groups affiliated with 7 departments in the form of 111 technical presentations — a testament to the breadth of research and diversity in MTL. The conference also offers three 10-minute plenary feature talks — a deviation from the parallel sessions in previous years intended to highlight some of the most exciting work this year. We encourage you to learn more about the latest research in eight diverse technical areas during the two poster sessions.

We are excited to announce two exceptional keynote speakers for MARC2018. Our evening keynote speaker is entrepreneur and private investor, Marina Hatsopoulous. Ms. Hatsopoulos' talk on "The Decisions of an Entrepreneur" will provide valuable insights into taking research from lab to the real world. Our morning speaker is Dr. Christopher Monroe, professor at University of Maryland and founder and chief scientist at IonQ, Inc. Dr. Monroe will give a talk on "Quantum Computing with Trapped Atomic Ions" and speculate the design of a universal quantum computing device.

MARC2018 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 MARC2018. We are also thankful for the leadership of MTL Director, Jesús del Alamo, the guidance of industry advisor, Nerissa Draeger, 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 MARC2018!

Sincerely,
Preet Garcha, Ben Lienhard,
and the MARC2018 Committee

MAKING A *MARC* ON HISTORY

MARC has evolved tremendously over time. It has been adorned with several names and been held at various different venues over the course of approximately three decades, with some new enhancements added every year. 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 MARC2018, 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 turned 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 has 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. This year marks the five-year anniversary of featured talks that were introduced to MARC in 2013. MARC2016 introduced the popular "Escape the Lab" game, and 2017 saw the advent of 2-minute MIG member pitches. This year continues these successful trends and advances them with plenary feature talks, even-odd poster sessions, night-before practice sessions, and other behind-the-scene upgrades.

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

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 activities from skiing/snowboarding on Mount Washington to 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
3:00 pm–4:00 pm	**Hotel Tour** Omni Mt. Washington Resort Optional for those arriving on the Early Bus from MIT.
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–7:30 pm	**Dinner Banquet** Grand Ballroom
7:30 pm–8:15 pm	**Evening Keynote** Grand Ballroom Marina Hatsopoulos, Entrepreneur, Director, Angel Investor “The Decisions of an Entrepreneur”
8:15 pm–8:45 pm	**Group Photo** Grand Ballroom
8:45 pm–Midnight	**Evening Activities** Washington, Jefferson, and Reagan Rooms Various group activities planned for the enjoyment and participation of all attendees, including the return of “Escape the Lab.” The Poster Pitch practice sessions will take place in the Presidential Ballroom.

AGENDA

DAY 2: JANUARY 30

7:00 am–8:00 am	**Breakfast** Presidential Foyer
8:00 am–8:15 am	**Opening Remarks** Presidential Ballroom The technical portion of the conference begins with remarks from MTL Director Jesús del Alamo and the MARC2018 co-chairs, Preet Garcha and Benjamin Lienhard.
8:15 am–8:45 am	**Technical Keynote** Presidential Ballroom Prof. Christopher Monroe, Bice Zorn Professor, University of Maryland and IonQ, Inc. “Quantum Computing with Trapped Atomic Ions”
8:45 am–9:15 am	**Two-Minute Pitch from MIG Members** Presidential Ballroom
9:15 am–10:00 am	**60-Second Poster Pitch, Sessions 1-3** Presidential Ballroom
10:00 am–10:15 am	**Coffee Break** Presidential Foyer
10:15 am–11:30 am	**60-Second Poster Pitch, Sessions 4-8** Presidential Ballroom
11:45 am–1:00pm	**MIG Networking Lunch** Dining Room/Sun Dining Room
1:00 pm–2:00 pm	**Poster Session 1** Grand Ballroom
2:00 pm–2:15 pm	**Coffee Break** Grand Ballroom area
2:15 pm–3:15 pm	**Poster Session 2** Grand Ballroom
3:30 pm–4:00 pm	**Plenary Featured Talks** Presidential Ballroom Three plenary featured talks chosen from abstracts submitted by the student and postdoc poster presenters.
4:00 pm–4:30 pm	**Closing Ceremony** Presidential Ballroom Award presentations and a final note from our organizers.
4:30 pm	**Buses Depart for MIT** Hotel Main Entrance Buses will depart for MIT at 4:45 pm.

DAY 1: EVENING KEYNOTE

“THE DECISIONS OF AN ENTREPRENEUR”

MARINA HATSOPOULOS

Entrepreneur, Director,
& Angel Investor

In creating value through innovation, an entrepreneur is by definition doing something novel, which means there isn’t a playbook to follow, and the entrepreneur often has to make things up and break the rules of convention by making his or her own critical strategic decisions, all of which will ultimately determine the success (or failure) of the endeavor. What a successful entrepreneur learns to do is to recognize strategic decisions, and how to use time, thought and information to make the best decisions.

MARINA HATSOPOULOS was Founding CEO and original investor in Z Corporation, an early market leader in 3D printing, from 1994 through its sale in 2005, when it reached $30 million in revenues. She is Chairperson of the Board and investor in Levitronix Technologies, the worldwide leader in magnetically-levitated bearingless motor technology. She is on the Advisory Board of the Nantucket [technology] Conference, and MIT Enterprise Forum Greece, as well as the EGG and OK!Thess acceleration programs in Greece. She is an investor in codebender and RTsafe, both based in Greece, and C2Sense, based in Cambridge, MA. She was a Director and investor in Cynosure Inc., a $400 million leader in the laser aesthetics market, which was sold for $1.65B. She was also a Director of the GSI Group, a $300 million supplier of laser-based equipment, and Contex Holding, a $100 million leading manufacturer of large-format scanners. She was an investor and Director of Dear Kate performance apparel and Tea Forte, a luxury tea brand which was sold to Sara Lee. She holds B.A. degrees from Brown University in Math and in Music, and an M.S. from the Massachusetts Institute of Technology in Mechanical Engineering.

DAY 2: MORNING KEYNOTE

"QUANTUM COMPUTING WITH TRAPPED ATOMIC IONS"

Individual atoms are standards for quantum information technology, acting as qubits that have unsurpassed levels of quantum coherence, can be replicated and scaled with the atomic clock accuracy, and allow near-perfect measurement. Atomic ions are confined by silicon-based chip traps with lithographically-defined electrodes under high vacuum. Quantum gate operations between atomic ions are mediated with control laser beams, allowing the qubit connectivity graph to be reconfigured and optimally adapted to a given algorithm or mode of computing. Existing work has shown >99.9% fidelity operations, fully-connected control with up to about 10 qubits, and quantum simulations with more limited control on up to 50 qubits—all with the same atomic architecture. Prof. Monroe will speculate on combining all of this into a single universal quantum computing device that can be co-designed with future applications, and how systems engineering will play out in the conventionally academic subject of quantum computing.

CHRISTOPHER MONROE

Atomic Physicist &
Quantum Information Scientist
University of Maryland
& IonQ, Inc.

CHRISTOPHER MONROE is a leading atomic physicist and quantum information scientist. He demonstrated the first quantum gate in any hardware at NIST in the 1990s, and at U. Michigan and U. Maryland since 2000 he discovered new ways to scale trapped ion qubits and simplify their control with semiconductor chip traps, simplified pulsed lasers, and photonic interfaces for long-distance entanglement. He is Co-Founder and Chief Scientist at IonQ, a start-up company that aims to build prototype quantum computer based in College Park, MD. Monroe is a member of the US National Academy of Sciences.

PLENARY FEATURED TALKS

DIVYA PANCHANATHAN

"Gas Spreading on Superhydrophobic Surfaces Immersed Underwater"

Find abstract on page 39

AVISHEK BISWAS

"In-Memory Computation for Low-Power Machine-Learning Applications"

Find abstract on page 18

REYU SAKAKIBARA

"Critical Design Parameters for Omnidirectional 2D Filled Photonic Crystal Selective Emitter for Thermophotovoltaics"

Find abstract on page 25

These three plenary featured talks were chosen from abstracts submitted by the MARC2018 student and postdoc poster presenters. This session will take place in the Presidential Ballroom on Day 2.

MIG MEMBER COMPANIES

Analog Devices, Inc.
Applied Materials
Draper
DSM
Edwards Vacuum
Foxconn Electronics
HARTING
Hitachi High-Technologies
IBM
Lam Research Co.
NEC
Qualcomm
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: ELECTRONIC & QUANTUM DEVICES

SESSION 2: CIRCUITS & INTEGRATED ELECTRONICS

SESSION 3: ENERGY-EFFICIENT CIRCUITS & SYSTEMS

SESSION 4: PHOTONICS & OPTOELECTRONICS

SESSION 5: ENERGY HARVESTING & STORAGE

SESSION 6: NANOTECHNOLOGY & NANOMATERIALS

SESSION 7: MATERIALS & MANUFACTURING

SESSION 8: MEDICAL DEVICES & BIOTECHNOLOGY

Xiaowei Cai
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Seeking summer internship.
PhD advised by Jesús del Alamo.
Available from June 2018.

Research Interests: Electronic devices, optoelectronics, quantum devices, nanotechnology, III-Vs, sensors, displays.

Impact of Channel Thickness on Transport in InGaAs Quantum-Well MOSFETs

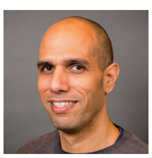
1.01

X. Cai, J. A. del Alamo

Sponsorship: Defense Threat Reduction Agency, Lam Research Corporation

InGaAs has emerged as a promising n-channel material candidate for future nano-scale CMOS thanks to its low voltage operation and superior electron transport properties. To explore the potential of InGaAs technology for sub-7 nm logic node, it is important to understand the intrinsic device performance scaling and underlying physics, resulting from physical dimension scaling.

In our research, we study the impact of channel thickness on transport in planar InGaAs MOSFETs. This is as a proxy to understanding the impact of fin width in future InGaAs FinFETs. We have prepared planar InGaAs MOSFETs with different channel thicknesses from 8 nm to 2 nm. They are fabricated by a planar self-aligned, contact-first, gate-last InGaAs MOSFET technology that involves a combination of reactive ion etching and digital etch. Through gated Hall and CV measurements, we have extracted the mobility as a function of channel thickness. We have found that compared to Hall measurements, traditional CV measurements over-estimate electron channel charge as they are contaminated by non-mobile electron charge trapped in the gate oxide. As a result, they under-estimate the mobility. From Hall measurements, we have observed a reduction in Hall mobility by 2 times when the channel thickness decreases from 8 nm to 2 nm. Nevertheless, we obtain a peak Hall mobility of ~2500 $cm^2/V \cdot s$ for a 2 nm channel thickness.



Alon Vardi
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Research Scientist supervised by Jesús del Alamo.

Research Interests: Cool and hopefully useful electronic devices.

InGaAs FinFETs with 5-nm Fin Width

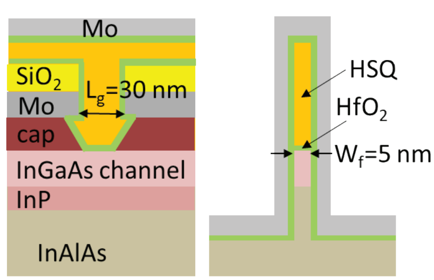
1.02

A. Vardi, J. A. del Alamo

Sponsorship: Defense Threat Reduction Agency, Lam Research Corporation, Center for Energy Efficient Electronics Science

InGaAs is a promising candidate as channel material for CMOS technologies beyond the 7 nm node. In this dimensional range, only high aspect-ratio (AR) 3D transistors with a fin or nanowire configuration can deliver the necessary performance. For future CMOS technology, the target fin width is 5 nm. In this work, we demonstrate for the first time III-V FinFETs with 5 nm fin width and record aspect ratio.

Our front-end process is CMOS-compatible that features only reactive-ion and digital etching to define the gate length and fin width. This yields high-aspect ratio InGaAs fins with smooth high quality sidewalls, self-aligned to the Ohmic contacts. By leveraging high-precision etching and a self-aligned design, we obtained the most aggressively scaled InGaAs FinFETs to date that also displays outstanding electrical characteristics. The electrical characteristics of a typical device with L_g = 50 nm and W_f=5 nm approach state of the art Si FinFETs with similar dimensions. Well-behaved characteristics and good sidewall control have been demonstrated.



◄ Schematic cross-section of InGaAs FinFET in L (left) and W (right) direction.

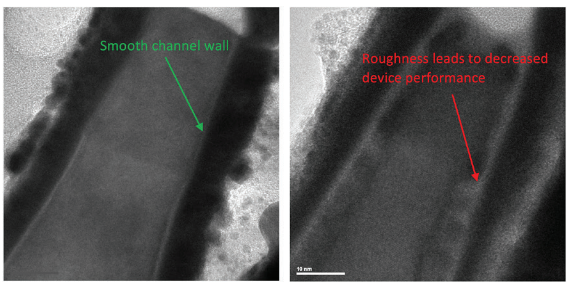
Characterizing and Improving Sidewall Roughness in III-V FinFETs

1.03

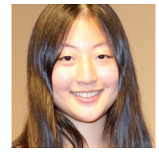
L. Kong, W. Lu, J. A. del Alamo

Sponsorship: UROP, Lam Research

III-V materials have great potential for integration into future CMOS technology due to their outstanding electron transport properties. InGaAs n-channel MOSFETs have already demonstrated promising characteristics, and the antimonide material system is emerging as a candidate for p-channel devices. As technology scales down to the sub-10nm nanometer regime, only transistors of a 3D configuration can deliver the necessary performance. III-V Fin Field-Effect Transistors (FinFETs) have displayed impressive characteristics, but have shown degradation in performance as the fin width is scaled to the sub-10nm regime. Using high-resolution transmission electron microscopy (HRTEM) to characterize interfacial properties between the channel semiconductor and the high-k gate dielectric along with electrical measurements, we show that high defect density, interdiffusion between the semiconductor and the dielectric, and roughness of the channel wall correlate with decreased device performance. We use atomic force microscopy to further characterize and understand the role of sidewall roughness in device performance.



◄ TEM images showing a good channel-dielectric interface (left) and rough interface (right).



Lisa Kong
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Seeking summer internship.
Undergraduate thesis advised by Jesús A. del Alamo.

Research Interests:
Nanomaterials, nanotechnology, electronic devices.

Towards Sub-10 nm Diameter Vertical Nanowire III-V CMOS

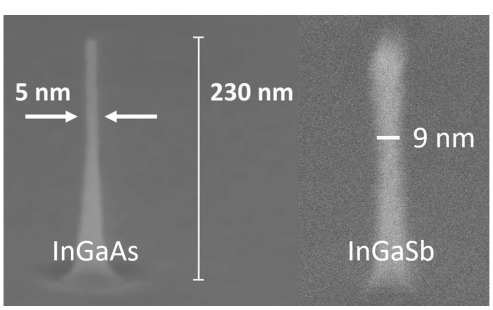
1.04

W. Lu, A. Vardi, X. Zhao, J. A. del Alamo

Sponsorship: Semiconductor Research Corporation, Defense Threat Reduction Agency, KIST, Lam Research

As CMOS technology keeps advancing, new material needed to replace Si. III-V compound semiconductors are promising channel materials for future technology. For example, InGaAs and InGaSb has superior electron and hole mobilities, indicating a way for III-V CMOS integration. One major challenge is precise control on transistor size at sub-10 nm.

In this work, we developed a process technology to fabricate InGaAs and InGaSb FinFETs and vertical nanowire MOSFETs with sub-10 nm fin width and nanowire diameter. The key is alcohol-based digital etch. It allows a consistent 1 nm/cycle etching rate on III-V heterostructures. We demonstrated record 5 nm diameter InGaAs nanowires and 9 nm diameter InGaSb nanowires. Recently, we fabricated InGaAs n-channel vertical nanowire MOSFETs with 7 nm diameter, and InGaSb p-channel FinFETs with 10 nm fin width. Both devices are first demonstrations at such small size with record performance. This work shows the potential of III-V CMOS technology.



◄ World's thinnest InGaAs and InGaSb vertical nanowires, with diameter of 5 nm and 9 nm, respectively.

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Seeking regular employment
PhD advised by Jesús del Alamo.
Available from June 2018.

Research Interests:
Electronic devices, CMOS technology, III-V semiconductors, analog IC design, nanotechnology.

Xin Zhao
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Technnovator

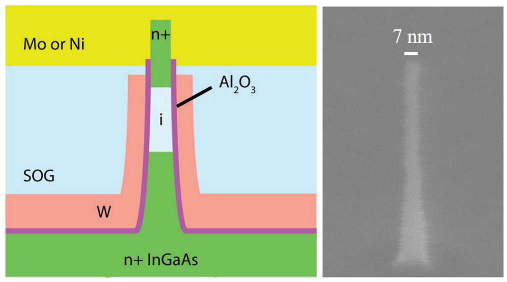
Research Interests:
Semiconductor device physics, design, fabrication and characterization, III-Vs, MEMS.

Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs

1.05

X. Zhao, C. Heidelberger, E. A. Fitzgerald, W. Lu, A. Vardi,J. A. del Alamo
Sponsorship: NSF Award 0959514, Lam Research and SRC (2016-LM-2655)

We present the smallest vertical transistors of any kind in any semiconductor system. These devices are sub- 10 nm diameter InGaAs vertical nanowire MOSFETs fabricated by a top-down approach, using reactive ion etching, alcohol-based digital etch and Ni alloyed contacts. A record ON current of 350 μA/μm at OFF current of 100 nA/μm and supply voltage of 0.5 V is obtained in a 7 nm diameter device. The same device exhibits a peak transconductance of 1.7 mS/μm and minimal subthreshold swing of 90 mV/dec at a drain voltage of 0.5 V, achieving the highest quality factor (defined as the ratio between transconductance and subthreshold swing) of 19 reported in vertical nanowire transistors. Excellent scaling behavior is observed with peak transconductance and ON current increasing as the diameter is shrunk down to 7 nm.



◄ Left: Schematics of the device cross-section of InGaAs vertical nanowire MOSFETs. Right: 7 nm diameter InGaAs nanowire used for device fabrication.

Ethan Lee
(ethanlee@mit.edu)
SM advised by Jesús A. del Alamo

Research Interests:
GaN FET, power electronics, dielectric reliability

Gate Dielectric Reliability under AC Stress in High-Voltage GaN Field-Effect Transistors

1.06

E. S. Lee, J. A. del Alamo
Sponsorship: Texas Instruments

Energy efficient electronics have been gaining attention as a solution to meet the growing demand for energy and sustainability. GaN field-effect transistors (FET) show great promise as high-voltage power transistors due to their ability to withstand a large voltage and carry large current. At the present time, the GaN metal-insulator-semiconductor high-electron-mobility-transistor (MIS-HEMT), the device of choice for electric power management, is limited from commercialization due to many challenges, including gate dielectric reliability. Under continued gate bias, the dielectric ultimately experiences a catastrophic breakdown that renders the transistor useless, a phenomenon called time-dependent dielectric breakdown (TDDB).

Our research aims to understand the physics of TDDB in GaN MIS-HEMTs. So far, efforts are focused on constant voltage stress due to the ease of experimental and instrumental setup. In contrast, our research aims to study the effects of applying AC stress to the gate. This mimics the real-world operating environment of FETs in power conversion circuits where they experience rapid transitions between the ON state and the OFF state.

In this work, we report the observation of an improvement in dielectric reliability under AC stress, as compared with DC stress, under identical gate bias and stress time. This improvement appears to be largely independent of frequency. These results, if confirmed, suggest a much better dielectric reliability of GaN MIS-HEMTs than previously believed.

AlN-Channel Metal-Semiconductor Field-Effect Transistors

1.07

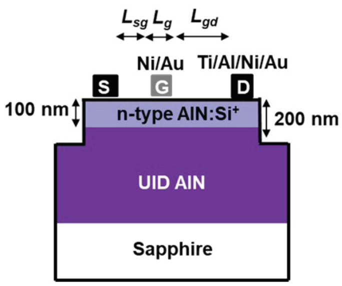
H. Okumura, J. Lemmettinen, S. Suihkonen, A. Uedono, T. Palacios

Sponsorship: Japan Society for the Promotion of Science

Hybrid-electric and full-electric vehicles have rapidly developed to counteract global warming caused by hydrocarbon combustion. These electric vehicles require DC-DC converters for the energy transfer between high and low voltage batteries. Wide band-gap semiconductor-based power devices would enable lower energy consumption and miniaturization of the power-units. Silicon-carbide DC-DC converters are already at the testing stage for hybrid-electric vehicles, showing confirmed improvement of fuel efficiency. Aluminum nitride (AlN) has the highest breakdown fields of 12 MV/cm, producing devices with lower resistance in the "ON" status, or higher energy efficiency. High-quality AlN films are commercially available. AlN electric devices are limited to Schottky-barrier diodes because AlN requires no polarization-induced doping to generate electron conduction. In this project, we achieved the first demonstration of AlN channel transistors using Si-ion implanted films. The AlN metal-semiconductor field-effect transistors show excellent operation of high-temperature and high break-down voltages.

Hironori Okumura
(okumura@mit.edu)
PhD advised by T. Kimoto and J. Suda. Postdoc at UCSB (J. Speck) and NTT (thin film group). Now assistant professor at Tsukuba Univ., working with EPFL (N. Grandjean) and MIT (T. Palacios). Available from April 2018.

Research Interests:
Crystal growth, Photonics, Electronic devices, III-Ns, III-Os.



◀ Schematic figure of AlN metal-semiconductor field effect transistors. AlN is grown on sapphire substrates by metal-organic chemical vapor deposition, followed by Si+ implantation and thermal annealing for n-type channel.

Nonvolatile Charge-Injection Memory Device Based on H-Terminated Diamond and Metal-Oxide Transfer Doping Layer

1.08

Y. T. Lee, A. Vardi, J. A. del Alamo

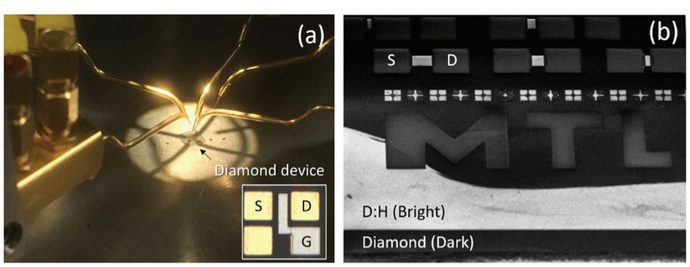
Sponsorship: Bose Foundation, US-Israel Binational Foundation

Diamond is considered the ultimate semiconductor material due to its distinctive properties such as outstanding critical breakdown field, thermal conductivity, hardness, broad optical transparency, and carrier mobility. For these reasons, significant effort was put towards study of diamond-based electronics in the 80~90s. However, device progress was hampered by the lack of suitable dopants with low activation energies. Recently, surface transfer doping (TD) of H-terminated diamond (D:H), prepared by either plasma or hot filament, has been reported. In surface TD, electrons from the valence band of diamond are transferred to the TD layer resulting in a 2DHG.

In this study, we report a novel transistor device based on D:H with WO_3 and HfO_2 layers. The D:H/WO_3 shows a strong p-type nature in ambient air with hole density of ~10^{13} cm^{-2} and Hall mobility of ~50 $cm^2V^{-1}s^{-1}$. Fabricated D:H/WO_3 transistors show a mobility (~12 $cm^2V^{-1}s^{-1}$), S.S. (~76 mV/dec) and on/off ratio (~10^6).

Young Tack Lee
(ytlee84@mit.edu)
Postdoctoral Associate supervised by Jesús A. del Alamo.

Research Interests:
H-Diamond, 2D materials, electronic devices, nanomaterials, nanotechnology, optoelectronics, sensors



◀ (a) Picture of D:H/WO_3 transistor under I-V measurement system. Inset is an optical microscope image of D:H transistor. (b) SEM image of D:H active after channel isolation. Bright area is D:H/TD surface and dark area is intrinsic diamond surface. The contrast suggests the strong conductivity of the 2DEG as a result of surface-transfer doping.

Deterministic Fabrication of Emitters in Photonic Circuits

1.09

M. Walsh, S. Mouradian, E. Bersin, N. Wan, D. Englund

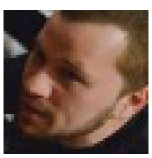
Sponsorship: Center for Integrated Quantum Materials, Center for Distributed Quantum Information

Michael Walsh
(mpwalsh@mit.edu)
PhD advised by Dirk Englund.
Available from May 2018.

Research Interests:
Communications, information processing, photonics, quantum devices.

The controlled creation of defect center-nanocavity systems is one of the outstanding challenges facing the development of an efficient interface between spin quantum memories and photons for photon-based entanglement operations in a quantum network. The process must also retain the optical and spin properties of the emitter. Here, we present a method that relies on autonomously imaging emitters in diamond and registering them relative to an on-chip coordinate system. This technique can be implemented on a large variety of emitter platforms, as it does not require a focused ion beam. The repeatability of this method suggests that the system operates with an accuracy down to ~30 nm. Once devices have been fabricated around pre-characterized emitters, an autonomous microscope system can be used to re-characterize the emitter-device systems such that only the best emitters are selected for transfer to the integrated photonic circuit.

This technique has the added benefit of providing statistically significant data sets at every step of the fabrication process, a feature that helps identify steps to improve the overall process. We take advantage of this to show that surface treatments/passivization can reduce the negative effects of fabrication on the optical properties of the emitter due to impurities on nearby surfaces. We also show that high temperature (1200 C) annealing can relieve fabrication induced strain in the diamond, further improving the optical properties of the emitter.



Sub-Diffraction Addressing of Multiple Quantum Defect Centers

1.10

E. Bersin, M. Walsh, M. Trusheim, S. Mouradian, D. Englund

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

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Available from May 2021.

Research Interests:
Quantum information, photonics, nanotechnology.

A scalable quantum computer will require both individual control and readout of multiple qubits, as well as a means of coupling them to facilitate the entanglement gates that are the hallmark of quantum supremacy. For optically active qubits such as quantum defect centers in solid state or trapped ions, these entanglement gates can come from optical interference measurements; however, these are often probabilistic and thus can be slow or of low fidelity. A more deterministic strategy is to use coupling of the electronic states, such as spin-spin or spin-orbit coupling. The exponential drop-off of this interaction strength mandates that the qubits be spatially co-located, generally well below the diffraction limit, making it difficult to have qubits that are both individually addressable and able to interact with one another.

We introduce a technique for unique readout that allows interrogation of multiple nitrogen vacancy (NV) defect centers in diamond. By taking advantage of the inherent strain gradients found in native diamond, we demonstrate the ability to selectively drive multiple strain-split resonance transitions in disparate NV centers. In particular, this method allows readout that is nondestructive towards the states of other NV centers in the diffraction spot. When combined with the fabrication of microwave striplines for spin qubit control, this system forms the first steps towards a qubit cluster that could serve as a small quantum computer, a logical qubit register in a larger error-corrected architecture, or a cluster of atomic sensors that could, as a collective, provide enhanced sensitivity. We highlight that this technique is not limited in application to NV centers, and can in principle be used with any solid-state system with a strain-dependent Hamiltonian.

Simultaneous Imaging of Top and Bottom Surfaces of a Sample in SEM

1.11

N. Abedzadeh, C-S. Kim, R. Hobbs, K. K. Berggren

Sponsorship: Gordon and Betty Moore Foundation

Imaging biomolecules in their natural state is crucial to the understanding of such molecules. Quantum electron microscopy (QEM) is a novel electron microscopy technique that proposes to achieve nanometer-scale resolution while practically eliminating beam-induced damage to biomolecules. A design for such a microscope requires an electron resonant cavity inside which repeated low-damage interactions between an electron and sample produces an image. Tetrode electron mirrors are proposed to be used in construction of such an electron cavity. In a proof-of-principle experiment, we demonstrated the operation of a single tetrode mirror inside an SEM. A micron-sized sample was placed below the objective lens of an SEM. The tetrode mirror placed below the sample reflected and refocused the scanning beam leading to simultaneous imaging of top and bottom surfaces of the sample. Integrating this design with a diffractive grating to form a loss-less reflective beam-splitter would be significant progress towards a complete QEM cavity.

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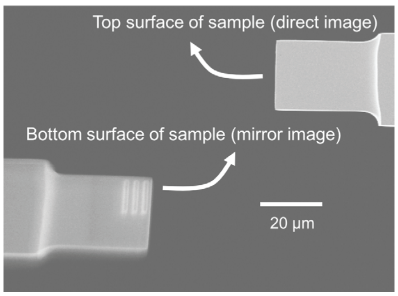
Research Interests:
Nanotechnology, photonics, quantum devices.



◄ Simultaneous imaging of top and bottom surfaces of a sample in SEM using a tetrode electron mirror, a component of an electron resonant cavity for QEM.

Room Temperature Spin-Orbit Torque Switching Induced by a Topological Insulator

1.12

J. Han, A. Richardella, S. A. Siddiqui, J. Finley, N. Samarth, L. Liu

Sponsorship: National Science Foundation

Recent studies on the topological insulators (TI) have attracted great attention due to the rich spin-orbit physics and promising applications in spintronic devices. In particular, the strongly spin-moment coupled electronic states have been extensively pursued to realize efficient spin-orbit torque (SOT) switching. However, so far current-induced magnetic switching with TI has been observed only at cryogenic temperatures. Whether the topologically protected electronic states in TI could benefit from spintronic applications at room temperature remains a controversial issue. In this work, we report SOT switching in a TI/ ferromagnet heterostructure with perpendicular magnetic anisotropy (PMA) at room temperature. Ferrimagnetic cobalt-terbium (CoTb) alloy with robust bulk PMA is directly grown on a classical TI material, Bi2Se3. The low switching current density provides definitive proof of the high SOT efficiency from TI and suggests the topological spin-momentum locking in TI even if it is neighbored by a strong ferromagnet. Furthermore, the effective spin Hall angle of TI is determined to be several times larger than commonly used heavy metals. Our results demonstrate the robustness of TI as an SOT switching material and provide an avenue towards applicable TI-based spintronic devices.

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Research Interests:
Spintronics

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Research Interests:
2D materials, electronic devices, nanotechnology, spintronics.

Ferrimagnetic Heusler Alloys for Fast, Energy-Efficient Spintronic Devices

1.13

J. Finley, L. Liu
Sponsorship: TSMC

Information storage using antiferromagnetically coupled materials instead of ferromagnetic materials promises to be more stable and secure, with higher switching speeds. Recently, we showed that the magnetic state in antiferromagnetically coupled cobalt-terbium alloys can be efficiently controlled, even when the net magnetic moment was close to zero. These ferrimagnetic films, however, are not ideal for practical spintronics devices due to the large magnetic damping, which increases the critical switching current. To overcome this, we instead explored the ferrimagnetic Heusler alloy Mn_2Ru_xGa.

In addition to being a ferrimagnet whose magnetization can be compensated by varying the Ru concentration, Mn_2Ru_xGa has also been shown to be a half metal, where one spin orientation behaves as a metal, but the other can behave as an insulator due to a band gap. This property allows Mn_2Ru_xGa to possess low damping along with potentially large spin-polarized current, resulting in large on-off ratios. We grew epitaxial films of Mn_2Ru_xGa on MgO substrates using magnetron sputtering. By varying the Ru concentration, we found the magnetic compensation point to be between $x = 0.64$ and 0.71 for 100 nm thick films. Generally threshold current density for switching is proportional to the magnetic layer thickness. Therefore, in order to achieve efficient switching we have grown films as thin as 5 nm that still possess magnetic ordering. To further reduce the film thickness and improve the magnetic properties, we have modified the strain in the system using different seed layers. Optimization of the magnetic properties in Mn_2Ru_xGa films and reduction of the film thickness promises fast, stable, and energy-efficient spintronic devices.

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Research Interests:
Electronic devices, nanotechnology, MEMS/NEMS.

A Four-Terminal Nanoelectromechanical Switch Based on Compressible Self-Assembled Molecules

1.14

J. Han, F. Niroui, J. Patil, T. Swager, J. H. Lang, V. Bulović
Sponsorship: National Science Foundation

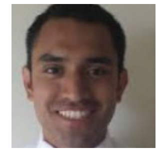
Nanoelectromechanical (NEM) switches are considered as promising candidates for future Internet-of-Things applications, due to their quasi-zero static leakage, large ON-OFF ratio, and high robustness in harsh environment. However, strong van der Waals interaction at the nanoscale usually results in high hysteresis and risk of stiction failure, thereby bringing about indispensable high actuation voltage and unfavorable dynamic power consumption in practical device designs. In this project, we developed a novel squeezable NEM switch, termed a "squitch", based on a metal-molecule-metal junction, whose tunneling gap can be modulated by compressing the molecule layer with electrostatic force induced by the voltage across the electrodes. With the help of these self-assembled molecules, direct contact of electrodes at ON-state can be avoided and hysteresis as well as possibility of stiction failure can be greatly reduced.

In this work, we present a four terminal squitch based on a chemically synthesized Au nanorod as the floating top electrode and bottom Au electrodes patterned with electron beam lithography. After applying a peeling approach we developed, the surface is planarized and sub-nanometer smoothness can be achieved. By choosing self-assembled molecules with different chain lengths, we are able to define precise nanometer-level junction, which can subsequently be adjusted by a body bias voltage at the first gate electrode. With the help of an appropriate body bias, we can exponentially modulate the conducting current by a sub-100 mV voltage applied at the second gate. The exceptional performance of our squitch device has been experimentally verified in terms of its low actuation voltage and hysteresis, which promises its prospect in ultra-low power digital logic applications.

Contactless Detection of Current in Industrial Connectors

1.15

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



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Available from January 2018.

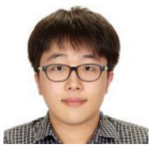
Research Interests:
Systems, Energy, Electronics

Contactless detection of the current in a conductor can be achieved by measuring the generated magnetic field. Other properties, such as the voltage and electrical power in the conductor, can similarly be inferred. The ability to measure these properties without disturbing an electrical system is desirable because it can facilitate the diagnosis of many aspects of the system, including power consumption, thermal output, and machine properties such as motor position.

In theory, current could be derived from magnetic field measurements through an application of Maxwell's equations. Unfortunately, in practice, there can be many other sources of electromagnetism in the environment that will interfere will the measured readings. Such sources include, but are not limited to, communication signals, electrical appliances, eddy currents in nearby conductors, and nearby permanent magnets.

We designed and constructed a system to detect currents despite electromagnetic interference. Our system consisted of 8 magnetic flux sensors attached to an industrial connector housing three lines of current. Our system, therefore, measured the total magnetic field generated by the 3 currents at 8 different locations.

We designed software to process the 8 readings while filtering out external electromagnetic interference. Our software multiplies a 3x8 matrix A by a vector containing the 8 magnetic flux measurements to yield three current estimates. We considered two alternative designs for the matrix. One alternative consisted of discretized solutions to Maxwell's equations that would find the least squares error estimation for the 3 currents from the 8 magnetic flux readings. The other alternative was a matrix generated using supervised learning algorithms that processed a training set we created. We implemented both systems and compared the accuracy of the results.



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Available from June 2021.
Research Interests: Analog-to-Digital Converter Designs.

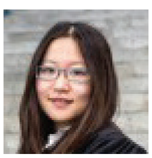
A Pipelined ADC with Low-Gain, Low-Bandwidth Op-amps

2.01

T. Jeong, A. P. Chandrakasan, H.-S. Lee
Sponsorship: Korea Foundation for Advanced Studies, MIT Center for Integrated Circuits and Systems, STMicroelectronics

Among various analog-to-digital converter (ADC) architectures, pipelined ADCs are well suited for applications that need medium to high resolution above hundreds-of-megahertz sampling rate. In order to obtain good linearity, conventional pipelined ADCs must minimize multiplying digital to analog converter (MDAC) charge-transfer error by employing high-gain, fast-settling op-amps. However, such an op-amp design has become increasingly difficult due to the reduced intrinsic gain and voltage headroom in a fine-line CMOS technology. With low intrinsic gain devices, either a gain-boosting technique or a multi-stage topology is necessary to make the op-amp meet the gain requirement. Decreased power supply demands a larger capacitance to maintain the same level of SNR. As a result, the power consumption of these op-amps becomes prohibitively large.

In order to address this issue, numerous techniques have been proposed. Op-amp non-idealities have been removed or relaxed in digital domain by taking advantage of digital computation. In some pipelined ADCs, analog circuit techniques have been invented to completely replace op-amps and use circuitry that is more amenable to scaled CMOS technologies. In this project, we propose a digital calibration scheme for op-amp-based pipelined ADCs. The ADC relaxes first stage op-amp performance requirements by using a shadow ADC and a simple digital domain calibration algorithm. To validate the functionality of the proposed calibration technique, a proof-of-concept ADC has been designed in 28nm CMOS technology and is currently being tested.



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Research Interests: Analog and mixed-signal integrated circuits and systems design.

A CMOS Flash ADC for GaN/CMOS Hybrid Continuous-Time Delta-Sigma Modulators

2.02

X. Yang, H.-S. Lee
Sponsorship: MIT GaN, ONR

High-speed and low-resolution flash analog-to-digital converters (ADCs) are widely used in applications such as 60-GHz receivers, serial links, and high-density disk drive systems, as well as in quantizers in delta-sigma ADCs. In this project, we propose a flash ADC with a reduced number of comparators by means of interpolation. One application for such a flash ADC is a hybrid gallium-nitride (GaN) and complementary metal-oxide semiconductor (CMOS) delta-sigma converter. The GaN first stage exploits the high-voltage property of GaN while the CMOS backend employs high-speed, low-voltage CMOS. This combination may achieve an unprecedented signal-to-noise ratio (SNR)/bandwidth combination by virtue of its high input signal range and high sampling rate.

One key component of such an ADC is a flash ADC. To take advantage of the high signal-to-thermal-noise ratio of the proposed system, the quantization noise must be made as small as possible. Therefore, a high-speed, 8-bit flash ADC is proposed for this system. Sixty-five comparators are used to achieve the six most significant bits. Sixty-four interpolators are inserted between the comparators to obtain two extra bits. The input capacitance of this design is 1/4 of a conventional 8-bit flash ADC. Therefore, a higher operating speed can be achieved. We introduced gating logic that enables only one interpolator during operation, which reduces power consumption significantly. A high-speed, low-power comparator with low noise and low offset requirements is a key building block in the design of a flash ADC. We chose a two-stage dynamic comparator because of its fast operation and low power consumption. With the scaling of CMOS technology, the offset voltage of the comparator keeps increasing due to greater transistor mismatch. In this project, we also propose a novel offset compensation method that eliminates the speed problem.

Data-Dependent SAR ADC

2.03

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

Sponsorship: MIT Center for Integrated Circuits and Systems

This work on successive-approximation-register (SAR) analog-to-digital converters (ADCs) aims at improving data-dependent savings in energy in key components of a SAR ADC by leveraging the information available from the signal's immediate past samples and the signal type. The dominant energy consuming components are the DAC and comparator. Energy expenditure in DAC per sample conversion depends on the DAC topology and sequence of steps taken during successive approximations. The energy in a comparator is directly proportional to the number of comparisons done per sample conversion. A design with data-dependent savings takes advantage of the correlation between successive samples in completing the conversion in fewer bit-cycles and also operates the DAC energy-efficiently.

Previous work presents data-dependent savings by doing least-significant-bit (LSB)-first successive approximation to convert an input sample. By starting with a previous sample and doing LSB-first, the algorithm converges in a fewer number of cycles than conventional most-significant-bit (MSB)-first SAR conversion. Fewer cycles translate into energy savings in the comparator and DAC. Another work developed successive approximation algorithms to find a sub-range from the full range in a few cycles before carrying on a binary search in this small range. In this work, we investigate a SAR ADC with a search algorithm based on the statistical characteristics of the signal for optimum energy expenditure.

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Research Interests: Data converters, mixed signal circuits.

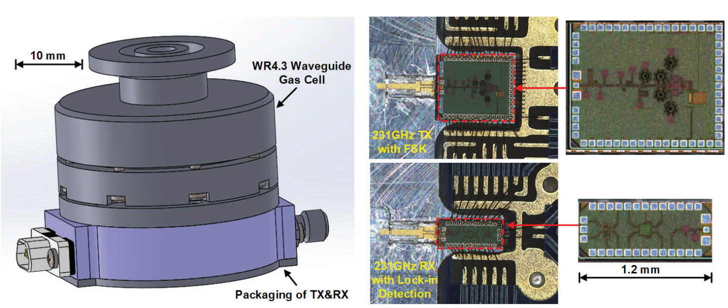
Molecular Clock on 65 nm CMOS: Precise Frequency Generation with Rapid Response

2.04

C. Wang, X. Yi, M. Kim, R. Han

Sponsorship: MIT Lincoln Laboratory

Rotational spectrometers based on Complementary Metal Oxide Semiconductor (CMOS) technology enables rapid, broadband and energy efficient gas sensing, which provides "finger print" identification for biomedical applications. It can also serve as accurate clock generator (molecular clock), due to the excellent quality factor and strong absorption intensity of the rotational spectral lines. Compared with chip scale atomic clock (CSAC) using vaporized Alkali atoms, the molecular clock (MC) has two key advantages: 1) it provides wider loop bandwidth due to broader absolute linewidth (bandwidth of 100 Hz~1 kHz in MC versus bandwidth of 1 Hz in CSAC), which enables rapid compensation for external disturbances; 2) it is environmentally insensitive, which reduces the difficulty for precise temperature control. Strong magnetic and electrical field shielding are also not necessary. A CMOS based molecular clock prototype based on 231.060983 GHz spectral line of Carbonyl Sulfide (OCS) has been developed using 65nm CMOS process. It shows promising stability, 53 mW power consumption, and low cost.



◂ Figure 1: The packaged molecular clock (left) and 231GHz transceiver inside implemented on 65nm CMOS process.

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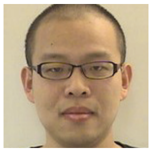
Research Interests: Spectroscopy, Radiator and Sensor, Imaging, Signal processing.



A 2D-Coupled 240-GHz Heterodyne Receiver Array for Digitally Beam-Steerable Sub-THz Imaging

2.05

Z. Hu, R. Han

Sponsorship: TSMC

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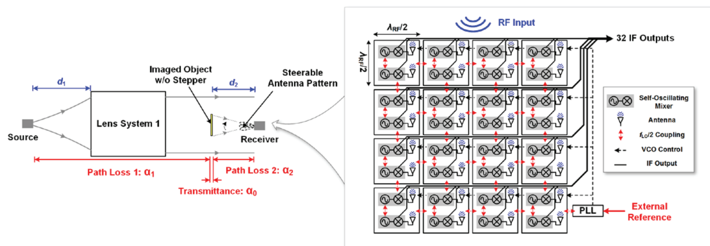
Available from June 2021.

Research Interests:
Terahertz sources, terahertz imagers.

Traditionally, terahertz imaging is performed using homodyne receivers that only capture amplitude information of normally incident waves transmitted through the imaged object. Therefore, for large-area imaging, low-efficiency mechanical scanning is required. In contrast, our imager (on 65nm CMOS), equipped with 4x4 heterodyne receiver array architecture, can work without mechanical scanning. By using heterodyne receivers, we are able to recover both phase and amplitude information of waves from any angle since local oscillation (LO) signal is phase locked. By placing receivers in a 2D $\lambda/2$-spaced fashion and providing them with synchronized LO signal, at baseband we can synthesize receiver antenna pattern pointing to any direction by weighting phase/amplitude to obtain the amplitude of transmitted wave at any location on the object (i.e., beam steering), making scanning process electrical. Design-wise, all receivers are compact and multifunctional—achieving LO generation, synchronization, and RF down-conversion simultaneously—which leads to high integration level.



◄ Set-up for beam-steerable imaging and architecture of our receiver chip.

Chip-Scale Ambient Quantum Magnetometry via CMOS Integration with Spin Ensembles

2.06

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

Sponsorship: MIT Center for Integrated Circuits and Systems

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Research Interests:
RFIC design, MW planar structures

There has been increasing interest in semi-conductor spin-based quantum sensors for a range of applications. Among these sensors, the nitrogen-vacancy centers (NV) in diamond have demonstrated outstanding ambient nanoscale sensing capabilities of magnetic fields, temperatures and electric fields. However, current approaches for NV-based quantum sensing have large form factor for microwave (MW) generation and optical readout, which can limit potential applications. To address these issues, we propose the integration of a Complementary-Metal-Oxide-Semiconductor (CMOS) architecture with NV centers. Thus, the system we propose is a promising platform for quantum sensing, which combines the compactness, scalability, and multi-functionality of CMOS technologies with the exceptional sensitivity of NV centers. This allows for a highly integrated quantum system with applications in the life sciences, tracking and advanced metrology.

In the proposed system, a chip-scale MW-optical interface controls and measures the NV spin ensembles for quantum magnetometry. Our system has an on-chip MW signal generator, operating from 2.6 GHz to 3 GHz. In addition, an on-chip coil with parasitic loops radiates the AC magnetic field with an amplitude up to 10 Gauss at 95% uniformity over the wide area of interest (50 µm by 50 µm). This microwave radiation efficiently manipulates the NV spin ensembles, which is followed by on-chip optical readout of the spin state. A CMOS-compatible metal-dielectric structures filters out the optical pump photons (532 nm) by coupling them to lossy surface-plasmon-polariton modes for an isolation of 10 dB. The red photons from the NV centers (signal) pass with 96% transmission. An on-chip patterned P+/N-Well photodiode, beneath the MW coil and filter, detects the NV red photons. This photodiode is patterned to reduce the unwanted coupling to the MW coil.

Chip Scale THz Radar for 3D Imaging

2.07

X. Yi, C. Wang, R. Han
Sponsorship: MIT Center for Integrated Circuits & Systems

Low cost 3D imaging recently became increasingly attractive because of its enormous potential security applications. Waves in the low-THz range provide powerful capabilities for imaging because they are not affected by light intensity and potential makeup coverage. Compared with RF and mm-wave frequencies, THz waves have a larger bandwidth and a shorter wavelength, which leads to higher range and angular resolutions. We proposed a novel comb radar architecture to improve the bandwidth to more than 100 GHz without using ultra-wideband components, i.e. using multi-tone frequency-modulated-continuous-wave signals and combining the intermediate frequency signals in the digital domain. In addition, both transmitter and receiver share the same on-chip antenna in one transceiver. According to our calculation and system simulation, about a 1 mm resolution can be achieved in this chip scale radar. The radar transceiver front-end including the antenna can be integrated on a single chip, making the solution low cost and lightweight.

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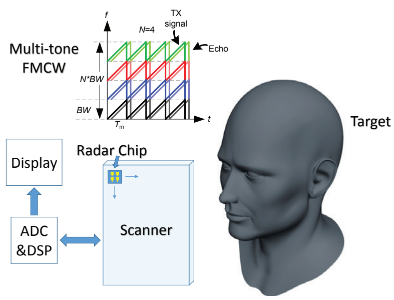
Available from July 2018.

Research Interests:
RF, mm-wave and THz frequency synthesizers and transceiver systems.

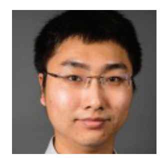


◄ Chip scale THz radar concept.

Miniaturized Front-End Stage Design for Low-Power AC-DC Converter

2.08

C. Zhang, D. J. Perreault
Sponsorship: FutureWei Technologies, Inc.



People always want smaller and lighter laptop chargers. Achieving higher efficiency of the converter is then critical because there are less volume to dissipate heat. State-of-the-art commercial product can reach 22W/inch^3 power density with peak efficiency higher than 90%. Converting AC to DC requires energy storage devices such as electrolytic capacitors, which contribute the most to the volume of the whole converter. Other major large components are inductors and EMI (Electromagnetic Interference) filters. To achieve higher power density and efficiency, we made a two-stage design. The front-end stage rectifies AC input and convert it into high-voltage DC bus. The back-end stage implementing VIRT (Variable Inverter/Rectifier/Transformer) technology steps down the voltage from DC bus and regulate to low voltage for output.

In the front-end stage design, AC input is firstly rectified and connected to a DC EMI filter instead of AC type because of the size. A boost type converter running in critical conduction mode brings the fluctuating input voltage to a fixed voltage level of 380V on the DC bus. The simple topology only costs very small count of components, and does not need high side driver. Running at a higher frequency results in smaller inductor size while not increasing switching loss because of the ZVS (Zero Voltage Switching) feature. High voltage DC bus gives better energy density on the buffer capacitor. Considering form factor of the available components, multilayer ceramic capacitor is selected which has a very good energy density and performance parameters. This circuit shapes line current for small buffer capacitor size, as the total power rating is lower than 75W and EN61000-3-2 is not applicable. The targeted energy density of our converter is 50W/inch^3 and overall efficiency is higher than 95%.

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Research Interests:
Inductively coupled wireless power transfer, power electronics

A High-Frequency Grid-Interface Power Converter

2.09

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Sponsorship: Fairchild Semiconductor

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Available from June 2020.

Research Interests:
Electronic devices, electronics, energy, energy harvesting devices & systems, GaN, III-Vs, integrated circuits, MEMS & NEMS, photovoltaics, power management.

Electrical loads process real power by drawing current at the same frequency as (and in phase with) the source voltage. Currents at other frequencies (e.g. harmonics) deliver no net energy to the load, but still dissipate energy in resistance in grid distribution lines and transformers. Regulations therefore require that grid-connected power converters draw currents with low harmonic content. Power conversion stages that draw compliant currents by design are called Power Factor Correction (PFC) converters.

Power factor correction converters are typically operated at low frequency to mitigate switching losses and to simplify control; this in turn requires large passive components. Soft switching techniques could permit higher frequency operation, but most soft-switched converters do not maintain high performance across the wide voltage and power ranges required for PFC applications. Here we present a PFC converter that enables high frequency operation by maintaining soft switching and by using a control scheme that requires no current sensing. These advantages are verified with a prototype, which achieves power factors above 0.996 and efficiencies around 97%. By using increased switching frequency (x10 over conventional designs), this converter can take advantage of greatly reduced passive component values for power conversion and filtering for electromagnetic compatibility.

Design Guidelines for Low-Loss High-Frequency AC Inductors

2.10

R. S. Yang, A. J. Hanson, C. R. Sullivan, D. J. Perreault

Sponsorship: National Science Foundation

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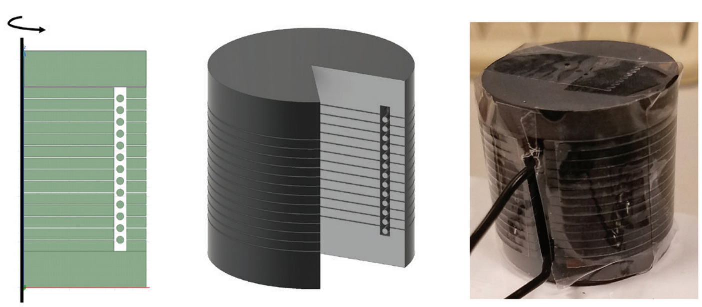
Research Interests:
Electronic devices, electronics, power electronics, power magnetics.

Operation in the High-Frequency (HF) regime (3–30MHz) has shown potential in miniaturizing power electronics, but substantial challenges in designing efficient miniaturized inductors at HF remain. Loss models for inductors at HF do not provide a clear direction for effective design, and many current design approaches rely on iterative optimization. We propose a low-loss inductor structure for constructing small, high-efficiency inductors at HF and introduce step-by-step design guidelines. An example 13.5 µH inductor (26.9mm diameter, 26mm height) designed using these guidelines achieved an experimental quality factor of 620 at 3MHz and 2A of AC current. We further demonstrate the low loss of the inductor in a high-ripple power converter operated at 1-3MHz; at 250W, the inductor improved converter efficiency by 1.2% compared to a conventional inductor design. Thus, the proposed inductor structure and design guidelines can reduce losses and thereby help realize high frequency miniaturization of power electronics.

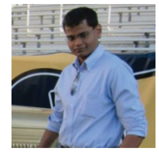


◀ Left: Radial cross-sectional view of the proposed inductor with core material encasing the winding.
◀ Middle: 3D model of the proposed inductor, created by revolving the left image about the axis (a piece is cut out for clarity)
◀ Right: 13.5 µH inductor prototype

Light-Weight Energy Harvesting from Transmission Lines

2.11

R. Kumar, J. L. Kirtley Jr., J. H. Lang



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PhD advised by James Kirtley and Jeffrey Lang.
Available from June 2019.

Research Interests:
Energy harvesting, battery modeling and estimation, high voltage power conversion.

Monitoring high-voltage transmission lines is vital in ensuring reliable power delivery. For example, in August 2003, inadequate tree trimming caused a short circuit which led to outages throughout the Northeast. Currently, transmission lines are inspected using helicopters tied to hundreds of kilovolts and operated by skilled personnel. To increase the effectiveness of transmission line monitoring, autonomous flying vehicles could be deployed to perform line inspection. This work explores two methods of harvesting energy from the transmission line itself to power autonomous line monitoring vehicles for continuous monitoring. In particular, the two modes of energy harvesting are magnetic-field and electric-field based methods. For a magnetic-field based energy harvester, using core materials with high magnetic permeabilities and saturation levels, an average power-to-weight number of 7.3 W/kg on a 100A transmission line is shown. The specific power could be higher given higher line currents, but the power-to-weight figure does not scale linearly. For example, if the line current is 1kA, an average power-to-weight of 31 W/kg can be expected.

For the electric-field based harvester, a multi-stage voltage step-down approach is used. The first stage of step down is a capacitive divider between the device and the capacitive coupling of the autonomous vehicle to ground. Then, a resonant switched capacitor topology was used to perform 3 kV to 500V DC-DC voltage step-down. Finally, a LLC converter is used to perform a 500V to 10V DC-DC stepdown for the battery charger. The final power-to-weight metric for an electric-field based harvester is 70 W/kg. To achieve superior performance, the aircraft for the electric-field based harvester must be large, for example a 5m diameter blimp to harvest 100W of power. However, the size requirement of the blimp may be reduced if the power requirement is relaxed or the converter switching frequency is reduced.

MEMS-Based Energy Harvesting System for Machine Health Monitoring

2.12

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Sponsorship: Analog Devices, Inc.

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Research Interests:
Electromagnetics, power, sensors.

Vibration-based machine health monitoring is an efficient method for tracking machine performance and preventing unrecoverable plant failures. The essential machine health information is extracted from sensors on the vibrating parts of the equipment. The key challenges of designing such systems are: building sensors that can operate from low amplitude vibration signals, tolerance to machine and sensor manufacturing variations, small form-factor, designing low-power electronics for battery-less operation, and efficient power harvesting from low frequency (around 50 Hz) machine vibrations. Current efforts resulted in a MEMS-based electromagnetic harvester prototype capable of delivering 165 μW to a matched load at a resonance frequency of 45.7 Hz, and a power density of 382 $\mu W/cm^3$.

The harvester is a spring-mass system fabricated using standard Si-MEMS process that oscillates under external vibrations. Magnets forming the mass create time varying magnetic flux during translational motion. Voltage is induced in the coils above and below the plane of motion. The harvester is designed to have a matched translational resonance frequency of 50 Hz, and higher modes that are well separated in frequency. The associated power electronics are designed to deliver 50 μW to the load at 1.8 V regulated output voltage. A boost converter based on H-bridge topology is implemented for impedance tuning and reactive power conditioning to maximize power extraction under 5% harvester-resonant frequency variation caused by manufacturing tolerances. The current open circuit voltage amplitude generated is 145 mV, and the Meissner-oscillator start up circuit achieves cold start-up from ~100 mV under 5% off-resonance conditions. The integrated circuit implemented in the TSMC 180nm process can be co-packaged with the harvester and forms a compact energy harvesting system solution for machine health monitoring.

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Research Interests:
Hardware security, cryptography, low power circuits, computer architecture

Energy-Efficient Security Acceleration Core for IoT

3.01

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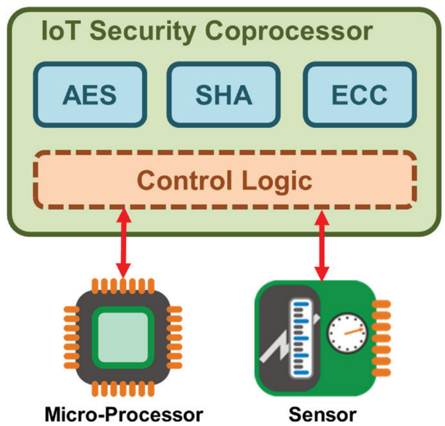
Sponsorship: Qualcomm Innovation Fellowship, Texas Instruments

The Internet of Things (IoT) has introduced a vision of the Internet where all computing and sensing devices are interconnected. However, these devices also have the potential to become attractive targets for cyber attackers, thus making IoT security a major concern. To achieve end-to-end security in IoT networks, public key algorithms like elliptic curve cryptography are indispensable. Software implementations of these algorithms involve significant computational costs, and the power consumption presents a bottleneck in resource-constrained environments. In this work, we demonstrate a low-power security-acceleration hardware to alleviate the security and efficiency trade-off observed in embedded devices.



◄ Security coprocessor for IoT to accelerate cryptographic primitives like AES, SHA and ECC. The hardware accelerator, which interfaces with a micro-processor, can be used to implement standard security protocols.

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Research Interests:
RF circuits, low power transceivers, RF security

A Low Power BLE-Compatible FSK Wake-Up Receiver for the Internet of Things

3.02

M. R. Abdelhamid, A. Paidmarri, A. P. Chandrakasan

Sponsorship: Delta Electronics

The Internet of Things (IoT) connects together an exponentially growing number of devices with an estimate of more than 70 billion devices in less than ten years from now. Such devices revolutionize the personal health monitoring, home automation systems, and industrial monitoring as well. Unfortunately, the wireless IoT nodes consume a huge portion of their energy on communicating with other devices. On the other hand, a longer battery lifetime or even a batteryless energy-harvesting operation requires a sub-microwatt consumption without significant performance degradation. In this work, we propose protocol optimizations as well as circuit level techniques in the design of an ultra low power wake-up receiver for on-demand communication with the IoT nodes.

Wireless protocols such as Bluetooth Low Energy (BLE) are optimized for short-length packets with small preambles and reduced header sizes. However, the power consumption of a low duty-cycled node in the default connected mode is limited by the periodic beacons dictated by the protocol. Commercial BLE chips are then limited to tens of microwatts even though their standby power is in the nanowatt range. The wake-up receiver exploits the lower limit of the standby power to achieve significant power reduction through a wake-up scheme wrapped around the BLE advertising packets transmission protocol. The receiver employs such duty-cycled wake-up protocol to mitigate the power/sensitivity tradeoff achieving sub-microwatt average power at the required BLE sensitivity. When the receiver decodes its wake-up pattern and generates a wake-up signal, it reconfigures its correlator with a new pattern. Such one-time patterns protect the node from energy draining attacks in the highly-congested IoT networks. With a commercial app, a user can wake the IoT node up using BLE packets while the receiver can trade off latency to scale down the average power consumption according to the application requirements.

Gazelle: A Fast Homomorphic Encryption Library for Accelerating Secure Neural Network Inference

3.03

C. Juvekar, V. Vaikuntanathan, A. P. Chandrakasan

Sponsorship: Delta Electronics, Qualcomm Innovation Fellowship

Fueled by a massive influx of data, sophisticated algorithms, and extensive computational resources, modern machine learning has found surprising applications in such diverse domains as medical diagnosis, facial recognition and credit risk assessment. In particular, state-of-art accuracies achieved by neural network based learning techniques have made them the solution of choice for solving many challenging problems. The predictive power of these networks makes a strong case for web-based services where domain experts can design neural networks to provide users with predictions for a small fee. A particularly compelling example is health-care where these web-based neural networks can help patients diagnose their ailments.

Unfortunately, two major challenges hinder adoption: first, the users of this service will rightfully be concerned about the privacy of the medical data that they provide such a service; and secondly, the service providers themselves would want to protect the privacy of their models as they wish to monetize them. As neither party is willing to share their inputs with the other we are at a natural impasse. Our work resolves this exact problem through a new protocol for the secure neural network inference that guarantees the privacy of the inputs from both parties.

We achieve this through combination of a fast additively homomorphic encryption scheme with classical two-party computation approaches like garbled circuits. Our optimized library allows us to compute on encrypted data while offering 2-3 orders of magnitude reduction in the communication bandwidth, roughly 10x reduction in run-time and works with existing networks without the need for any retraining.

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Research Interests:
Electronics, information processing, integrated circuits, systems, hardware security.

Low-Power Speaker ID with Low-Precision Neural Networks

3.04

S. Koppula, J. Glass, A. P. Chandrakasan

Sponsorship: MIT

Power-consumption in small devices is dominated by off-chip memory accesses. The task of speaker ID, verifying identity of a person through their speech samples, traditionally has required use of neural networks larger than 10 MB for state-of-art performance. By decreasing the size of speaker ID models to fit in on-chip memory, we can perform end-to-end inference without off-chip memory access, improving energy performance of speech accelerators for speaker ID.

First, we demonstrate that use of learned weight and activation quantization to reduce numeric precision in speaker ID networks is an effective way to reduce model size, but retain competitive identification accuracy. For example, according to our benchmarks, parameter quantization to 28-bits (a 12% decrease in bytesize) yields no loss in accuracy for state-of-art CNN architectures, and quantization down to 4-bits (92% decrease in bytesize) yields a 8% drop in accuracy. Concurrent to model size reductions, our precision-reducing training procedure also affords circuit-area advantages, requiring only smaller, lower-bitwidth arithmetic units. Additionally, we are able to remove the need for fixed-point or floating-point operations during network inference by constraining our optimization problem during training to unsigned integers. The use of a new type of convolution, depthwise-separable convolution, has yielded an additional 16% model size reduction.

Our megabyte-sized model comfortably fits in the on-chip BRAM for most off-the-shelf FPGAs. Currently, we are implementing this work on a Xilinx Virtex-6. We have three separate components in this design. First, we collect raw audio samples from the on-board microphone. We perform front-end signal processing (DCT/Mel filterbanks) then evaluate our quantized neural network in programmable logic.

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Research Interests: Systems, Digital Architecture, Machine Learning, Speech, Multimedia Applications

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Research Interests:
Communications, Information processing, Integrated circuits, Multimedia, Systems.

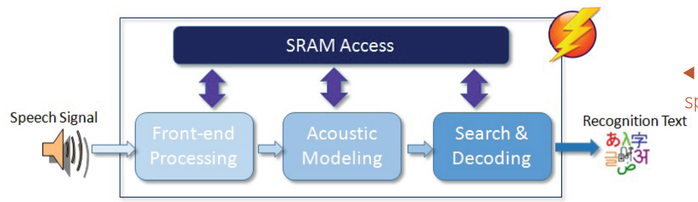
Small-Footprint Speech Recognition Circuits

3.05

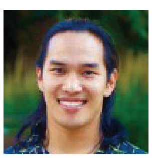
D.-C. Chueh, A. P. Chandrakasan

Sponsorship: Foxconn Technology Group

With the advancement technology of speech and natural language processing, spoken language has become a feasible way for human machine interaction. Due to the high complexity of articulated speech signal, automatic speech recognition (ASR) generally requires intensive computation and memory size. However, due to its applications on robots, wearables, and mobile devices, it's desirable to design a circuit to implement ASR locally in a resource-limited environment. In this work, we design a small-footprint ASR system with a cutting-edge neural network that can perform acoustic modeling with memory restrictions, weight truncation and quantization. We implement a weighted finite-state transducer (WFST) to incorporate the phonetic probability with a language model to select the best word transcription. Compression, caching, and lattice truncation are adopted to adapt the ASR to circuit and optimize the design. This design demonstrates the feasibility to operate an ASR in a small-footprint environment in applications with small vocabulary size and simpler model.



◄ Block diagram of automatic speech recognizer design.



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Research Interests: Analog AI, algorithm for AI, cognitive computing, resistive switching, neuromorphic devices

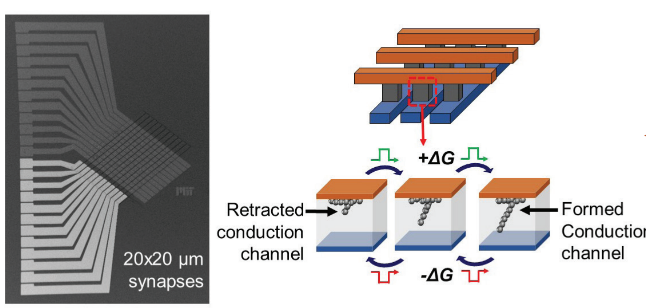
Epitaxial Memory as Suitable Platform for Large-Scale Neuromorphic Arrays

3.06

S. Tan, S. H. Choi, Z. Li, Y. Kim, C. Choi, P.-Y. Chen, H. Yeon, S. Yu, J. Kim

Artificial Intelligence (AI) is revolutionizing how we learn, connect, and experience the world. Neural networks have enabled many new technologies; however, conventional computing architectures consume excessive amounts of power. New platforms specialized for AI are neccessary to solve this energy challenge as Moore's law reaches an end.

We have developed epitaxial random access memory (epiRAM) as a hardware platform for a brain-inspired neuromorphic computing system. Synaptic weights in neural network algorithms can be represented by conductance states of epiRAM devices at array crosspoints. Metallic conduction channel evolution is confined in one-dimension for linear and gradual artificial synapse conductance change during neural network training. Semiconductor layers allow self-rectification to reduce sneak currents. Set voltage and read currents can be tuned by adjusting the Schottky barrier at the p+ Si/ Ag conduction channel interface. EpiRAM in passive crossbar arrays can be trained for handwriting digit recognition with up to 95.1% accuracy.



◄ SEM image of an epiRAM crossbar array and an illustration of conduction channel evolution during neural network training.

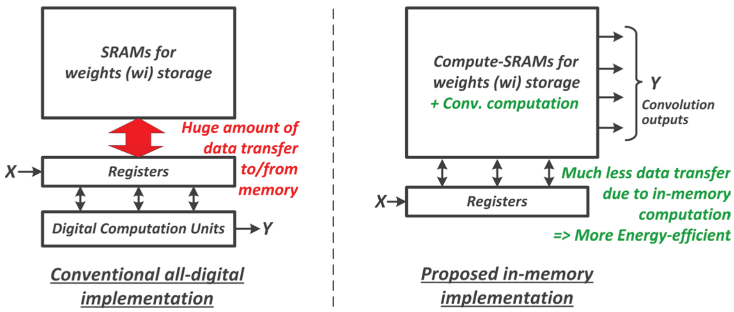
In-Memory Computation for Low-Power Machine-Learning Applications

3.07

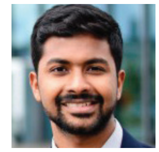
A. Biswas, A. P. Chandrakasan

Sponsorship: Intel Corporation

Convolutional Neural Networks (CNN) have emerged to provide the best results in a wide variety of machine-learning (ML) applications, ranging from image classification to speech recognition. However, they require huge amounts of computation and storage. When implemented in the conventional Von-Neumann computing architecture, there is a lot of data movement per computation between the memory and the processing elements. This leads to a huge power consumption and long computation time, limited by the bandwidth of the memory, making it unsuitable for many energy-constrained applications such as smartphones, wearable devices. Our approach is to make the memory more proactive in the computation to address these challenges. If we can embed some computation capability in the memory then there would be much less data transfer and also the potential to process multiple memory address in parallel to increase throughput. This could enable low power ubiquitous ML applications for a smart Internet-of-Everything.



◄ Concept of the proposed in-memory computation using a standard SRAM array.



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Available from June 2018.

Research Interests:
Low-power SRAM, in-memory computing, non-volatile memory

Efficient Processing for Deep Neural Networks

3.08

Y. N. Wu, T.-J. Yang, Y-H. Chen, J. Emer, V. Sze

Sponsorship: DARPA YFA, MIT CICS, Intel, Nvidia

Artificial Intelligence powered by deep neural networks (DNNs) has shown great potential to help a wide range of industry sectors with unprecedented performance. Deploying DNNs into the field, therefore, becomes the next research frontier due to the high computational complexity of DNNs. Specifically, energy efficiency has an ever-increasing importance compared to other requirements, such as throughput and accuracy, due to the boost in battery-powered devices for IoT and the exploding computation intensity in data centers. However, currently there is no standard or protocol to follow for DNN processing; the fast-moving pace in new DNN algorithm and application development also requires the hardware to stay highly flexible for different configurations. These factors open up a large design space of potential solutions with optimized efficiency, and a systematic approach to this problem becomes very crucial.

To solve this problem, we present a series of work to address the co-optimization among the three most important pillars in the design of DNN processing systems: architecture, algorithm and implementation. First, we present Eyeriss, a fabricated chip that implements a novel dataflow architecture targeting energy-efficient data movement in the processing of DNNs based on state-of-the-art DNN algorithms. It demonstrated over 10 times higher energy efficiency over mobile GPUs that are widely benchmarked for such task. Second, based on the desired hardware features learned from the Eyeriss implementation, we develop Energy-Aware Pruning (EAP), a new strategy of removing weights in the network to reduce computation so that it becomes more hardware-friendly and yields higher energy efficiency. EAP demonstrates 3.7 and 1.7 times higher energy efficiency compared to the unpruned DNNs and DNNs pruned with conventional methodologies, respectively. Finally, given the prior knowledge of the Eyeriss implementation and the EAP algorithm co-optimization, we present a tool to realize fast exploration of the architecture design space under different implementation and algorithmic constraints.

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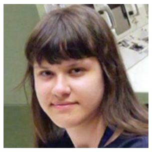
Research Interests:
Energy efficient computer architecture, computer systems, deep learning



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Research Interests:
Information processing, integrated circuits, multimedia, systems.

Energy-Efficient Deep Neural Network for Depth Map Reconstruction

3.09

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Sponsorship: Analog Devices, Inc.

Depth sensing and estimation is a key aspect of positional and navigational systems in autonomous vehicles and robots. The ability to accurately reconstruct a dense depth map of a surrounding environment from RGB imagery and sparse depth data is necessary for successful obstacle detection and motion planning. Since deep convolutional neural networks (DNNs) have proven to be successful at achieving high accuracy rates in image classification and regression, recent work in the deep learning space has focused on designing neural networks for depth prediction applications. However, the high accuracy of DNN processing comes at the cost of high computational complexity and energy consumption, and most current DNN designs are unsuitable for low-power applications in miniaturized robotics.

In this project, we aim to address this gap by applying recently developed methodologies for estimating and improving the energy-efficiency of DNNs to an existing depth-prediction DNN. We envision an outcome in which the depth-prediction DNN is modified to be better suited for a specialized hardware implementation that could be integrated with a low-power visual-inertial odometry system to result in a combined navigational system for miniaturized robots.

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Available Summer 2019

Research Interests:
Depth estimation, physics-based computer vision, computational imaging, machine learning

Low Power Dynamic Depth Estimation of Time-of-Flight Imaging

3.10

J. Noraky, V. Sze

Sponsorship: Analog Devices, Inc.

Depth sensing is used in a variety of applications that range from augmented reality to robotics. One way to measure depth is with 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 in one shot and with minimal computation. However, many of the applications that use depth also run on battery powered devices, and the illumination source of a TOF camera further limits its battery life.

To minimize the power required for depth sensing, we present an algorithm that uses images, which are routinely collected alongside the TOF camera, to estimate a new depth map without illuminating the scene. In our previous work, we presented an algorithm to estimate the depth in static scenes, a scenario common for applications like robotic navigation. Here, we extend our approach to handle dynamic environments. While every point in a dynamic scene can, in principle, move independently, most natural environments are composed of multiple, nearly-rigid objects. Our technique exploits this insight and uses the collected images to estimate the most rigid 3D motion to explain the pixel-wise displacements from which a semi-dense depth map can be obtained. Our algorithm is best suited for applications where depth is not required at every pixel (e.g. gesture estimation) and can be used with depth infilling approaches to obtain a dense depth map. Our technique is also computationally inexpensive, does not require the rigid objects to be segmented, and estimates the 3D motion directly from the pixel data. To demonstrate the accuracy of our approach, we present results on both synthetic and real data.

Fast Frontier Exploration for Unmanned Autonomous Vehicles with Resource Constraints

3.11

Z. Zhang, S. Karaman, V. Sze

Sponsorship: U.S. Air Force Research

Unmanned Autonomous Vehicles (UAVs) have received widespread attention. Their capability to navigate around the environment enables a lot of applications including search-and-rescue, surveillance, wild life protection and environment mapping. The key technique to empower such capabilities is the frontier-exploration algorithm, which periodically makes decisions on where the vehicle should explore next in an unknown environment given the knowledge it has acquired before. However, such algorithms are computationally expensive. In a practical system, the algorithm is usually off-loaded to a power computer, causing a huge delay in the decision time and a strong dependence of the system on stable and fast internet connections. This prohibits the application of the frontier-exploration algorithm to resource-constrained small UAVs with limited battery and computation power.

In this work, we present an algorithm to significantly reduce the computation cost of the state-of-the-art mutual information-based frontier exploration algorithm. As a benefit, the algorithm can run locally on battery powered devices, reducing the delay and allowing the vehicles to explore faster and longer. The innovation is based on the following two techniques: the first is to leverage the shared computation of the mutual information between a sensor beam and multiple map locations to reduce the redundant computations. The second technique is to compress the representation of the environment map so that the computation of the mutual information can be focused on the subpart of the map with highest relevance at an adaptively chosen scale.

We evaluate the performance of our system in a synthetic setup where a ground robot explores a set of 2D unknown environments. We compare both the number of operations as well as the running time of the system against the previous state-of-the-art. This proves its effectiveness to enable a battery powered vehicle to explore the unknown environment.

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Research Interests: Machine learning, computer vision, robotics, video processing, ASICs for vision and robotics.

NAVION: An Energy-Efficient Accelerator for Nano Drones Autonomous Navigation in GPS-Denied Environments

3.12

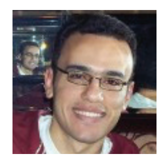
A. Suleiman, Z. Zhang, L. Carlone, S. Karaman, V. Sze

Sponsorship: Air Force Office of Scientific Research

Drones are getting increasingly popular nowadays, where it is reported that their sales have tripled in the last year. Nano drones specifically are easily portable and can fit in your pocket. Equipped with multiple sensors; like cameras and inertial measurement units (IMUs), the drone functionality is getting more powerful and smart (e.g., track objects, build accurate 3D maps and even avoid obstacles). These capabilities can be enabled by powerful computing platforms like CPUs and GPUs, which consume a lot of energy. Both the size of these platforms as well as their battery's weight prohibit deployment to nano drones, which can be as small as bottle caps and operate on very small batteries.

In this project we present NAVION, an energy-efficient hardware accelerator for nano drone autonomous navigation in GPS denied environments. The hardware is co-optimized with the algorithm and the drone design to enable a lightweight drone (~10s of grams). The nano drone is equipped with a stereo camera and an IMU, and can operate in real time without any external communications. NAVION accelerator's power consumption is in the range of the lifting power of nano drones, which is less than 100 mW.

The proposed accelerator implements a robust and optimized visual inertial odometry (VIO) algorithm. It combines the visual information and the IMU measurements to estimate the position, orientation and velocity of the nano drone as well as the 3D environment via the Gauss-Newton algorithm. The implementation takes advantage of hardware parallelism, pipelining and data statistics to achieve real-time performance and energy efficiency. This accelerator gives a nano drone the smart sensing capability which now only exists in large drones with bulky batteries. It enables numerous applications where large drones do not fit, such as rescuing from collapsed buildings, indoor exploration and surveillance.



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Available from June 2018.

Research Interests:
Synthesis and Optical and Electron Microscopy of Semiconductors

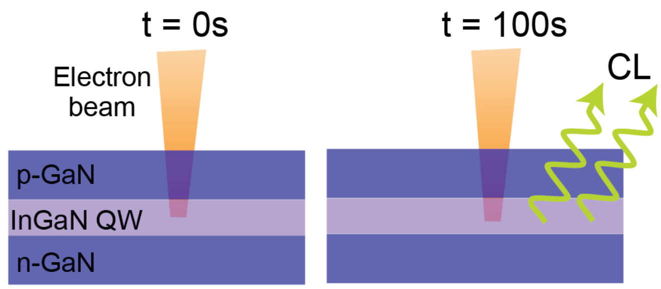
Carrier Transport and Deep Level Defects Lead to Delayed Cathodoluminescence in InGaN/GaN LEDs

4.01

A. Singh, Z. Zhao, J. Chesin, R. Armitage, I. Wildeson, A. Armstrong, K. Kisslinger, E. Stach, S. Gradečak

Sponsorship: DOE, Office of Energy Efficiency and Renewable Energy (EERE)

InGaN LEDs are the dominant solid state lighting solutions but suffer from efficiency droop at high injection currents. In this work, we use a combination of electron microscopy tools to investigate reduced-droop InGaN/GaN quantum well (QW) designs. We find that chip-scale efficiency is uncorrelated with extended well-width fluctuations observed in scanning transmission electron microscopy. Remarkably, delayed cathodoluminescence (CL) is observed from LEDs in which carriers are designed to easily escape from the QWs. We propose a model in which the electron beam (a) passivates deep level defect states and (b) drives charge carrier accumulation and subsequent reduction of the built-in field across the QW active region, resulting in delayed radiative recombination. Finally, we correlate CL rise dynamics with capacitance-voltage measurements, and show that certain early-time components of the CL dynamics are indicative of the open circuit carrier population within one or more QWs.



◂ Continuous electron beam irradiation measures no CL initially. Consequently, CL increases with time until steady state is reached.

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PhD advised by Silvija Gradečak.
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Research Interests:
GaN LEDs, Nanomaterials, 2D materials.

Electron Energy-Loss Spectroscopy of InGaN Quantum Well Light Emitting Diodes and Impact of Indium Distribution on Efficiency Droop

4.02

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

Indium gallium nitride (InGaN) quantum well (QW) light emitting diodes (LEDs) are wavelength-tunable and consist of InGaN QWs separated by GaN barriers. While LEDs have a 70% wall plug efficiency (WPE) compared to the 5% WPE of incandescent bulbs and 20% WPE of fluorescent bulbs, these devices suffer from efficiency droop, in which the quantum efficiency peaks at low injection currents and decreases monotonically with increasing current. Non-uniformity of indium composition within the QWs is one important factor that has been previously suggested to contribute to efficiency droop. Therefore, mitigating the efficiency droop to allow for large-scale applications of LEDs requires a multi-pronged approach that examines how device performance relates to composition and material fluctuations within the QWs.

We use electron energy-loss spectroscopy (EELS) to map indium composition along the QWs in high- and low-performing InGaN QW LEDs. EELS provides a compositional fingerprint of the QWs with near-lattice resolution and is less sensitive to surface modification by sample preparation methods. Therefore, EELS is well suited for evaluating the presence of compositional fluctuations on the nanometer scale. Here, we collect EELS maps of QW regions of the LEDs and develop a methodology for extracting compositional information from these spectra, which is non-trivial due to the overlap of indium and nitrogen peaks in the EELS spectra. A comparison of the indium signal variation in the QWs of both high- and low- performing devices reveals only a few fluctuations on the order of 1-2 nm that are greater than the noise floor. Our results indicate that further studies are needed to investigate the difference in device performance, which could be related to the QW interface quality QWs, material defects, fluctuations in the QW width, or other factors. Future work includes investigating samples with known indium fluctuations and correlating these fluctuations to device performance.

Metal-Organic Frameworks for Lanthanide Sensitization and Lasing Applications

4.03

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Sponsorship: Center for Excitonics

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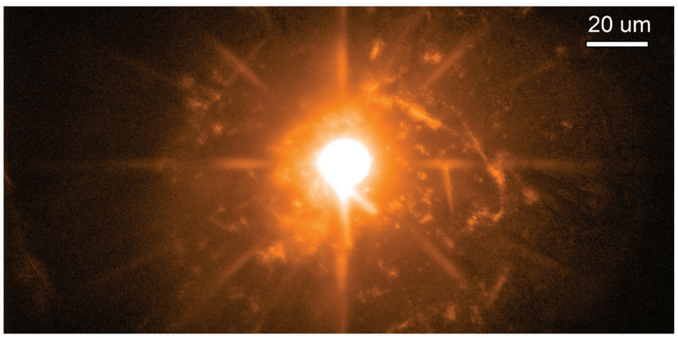
Available from April 2018.

Research Interests:
Novel light emitters, nanomaterials, metal-organic frameworks.

Metal-organic frameworks (MOFs) are well-ordered crystals formed through the coordination of metal ions by organic linker molecules. When lanthanide metal ions (e.g. Nd3+, Eu3+, Yb3+) are used as the coordinate metal, these materials bridge the gap between functional nano-structures and laser physics. Lanthanide ions are ideal laser emitters as they have well-defined emission wavelengths and are easily excited to the point of population inversion—a requirement for lasing. While lanthanides are poor light absorbers, they can be sensitized to optical excitation through the coordination of strongly absorbing organic molecules which transfer the absorbed energy to the lanthanide atom, known as the antenna effect. Here, the organic linker of choice (hexahydroxyphenylene) both sensitizes the lanthanide ions and produces nanorod structures when crystallized as a MOF. Upon photo-excitation, the nanorods act as a natural gain medium for the inverted lanthanide population and photon amplification occurs in the cavity-like structures.

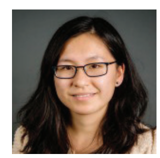


◄ Figure 1: False-color microscope image of ultrabright photoluminescence from a Europium-based metal-organic framework. Here, a 405 nm laser is used to excite nanorod structures which emit intense enough light to illuminate the surrounding sample surface.

Exciton Dynamics in Lead Sulfide Quantum Dots

4.04

W. Wu, W. A. Tisdale
Sponsorship: U.S. Department of Energy



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Available from August 2021.

Research Interests:
Nanomaterials, energy, energy harvesting devices & systems, light-emitting diodes, optoelectronics, photonics.

Colloidal quantum dots (QDs) are nanocrystal semiconductors with highly tunable band gaps. Lead sulfide (PbS) QDs are of particular interest because they absorb and emit near-infrared (NIR) light which can lead to applications of this material in devices such as solar cells, light emitting diodes (LED) and NIR detectors. Additionally, PbS QDs can serve as a sensitizer for photon upconversion process in single junction photovoltaics to potentially overcome the Shockley-Queisser limit. Further, carrier multiplication, meaning multiple free carriers or photons resulting from absorption of single high energy photon, can occur in PbS QD solids. This process can enhance photocurrent in photovoltaics, and amplify signals in biological sensors. To better engineer these devices, it is important to understand exciton transport in the QD solids. Past studies have shown exciton hopping in PbS QD solids occurs by Förster resonance energy transfer (FRET), which is due to interactions between weakly coupled transition dipoles on neighboring QDs.

A complication is that individual QDs in a macroscopic solid have slightly different sizes. The dependence of FRET rate on this QD polydispersity is poorly understood, as most studies to date have left QD polydispersity out of the picture due to synthetic methods having little control over this parameter. Recent advances in PbS QD synthesis have made it possible to control the polydispersity. We study how QD size dispersity affects the energy transport in the solids. In particular, temperature dependent spectrally-resolved transient photoluminescence spectroscopy provides much insight into exciton decay dynamics in PbS QD solids of varying polydispersity.

With this method, we observe the photoluminescence peak red shift over time to reach a thermodynamic equilibrium. Fitting this red shift using the Pauli master equation allows extraction of the exciton hopping parameters. These studies give us a better understanding of the energy transfer processes in PbS QD solids.

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Available from September 2019.

Research Interests:
Materials design, energy transfer, exciton dynamics

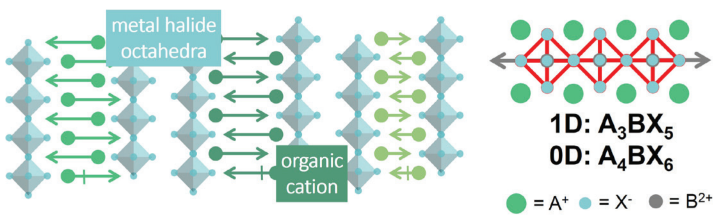
Exciton Dynamics in Low Dimensional Hybrid Perovskites

4.05

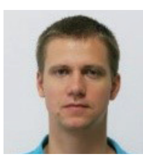
C. M. Mauck, W. A. Tisdale

Sponsorship: MIT Center for Excitonics

Interest in bulk perovskite structures for PV applications has exploded in the last five years, due to their low cost and solution-processable preparation, with a stunning increase in power conversion efficiency (PCE) over 20% since that time. Fewer studies have investigated the low dimensional perovskites, in particular the 0D and 1D-networked structures that have a much wider parameter space for structural tunability. In contrast to bulk 3D perovskites that display typically low exciton binding energies (E_b) and readily form free charge carriers, lower dimensional networked hybrid perovskites are excitonic materials, with high E_b and dielectric confinement of the metal halide octahedra within the organic sublattice. Here, we discuss how cation structure affects the optoelectronic properties of these bulk quantum-confined materials, with applications in displays, lighting, and lasing.



◂ Low dimensional networked perovskites have tunable band gaps varied by material composition. Structures are shown on the right for perovskites with octahedra linked along one dimension, and for 0D perovskites in which the metal octahedra are isolated within the organic sublattice.



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Available from December 2018.

Research Interests:
Novel electronic devices, physics of oxide materials, numerical simulations, optical absorption spectroscopy.

Reprogrammable Electro-Chemo-Optical Devices

4.06

D. Kalaev, H. L. Tuller

Sponsorship: U.S. Department of Energy, Basic Energy Sciences Program

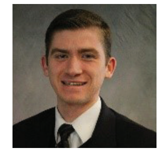
Photonic devices with programmable properties allow more flexibility in manipulation of light. Recently, several examples of reconfigurable photonic devices were demonstrated by controlling the local/overall index of refraction in thin films, either by thermally induced phase change in chalcogenides or by intercalation of lithium into oxides. We propose a novel approach for design of reprogrammable photonic devices based on electrochemical modification of ceria-based electro-chemo-optical devices. Previously, it was shown that the refractive index of $Pr_xCe_{1-x}O_{2-\delta}$ is a function of oxygen nonstoichiometry δ that can be controlled electrochemically via closely spaced electrodes in a lateral device configuration. For transverse modified configurations, a PCO thin film on yttrium stabilized zirconia substrate with transparent conducting electrode, top electrode allows for voltage controlled oxygen exchange. Enhanced spatial resolution can be further achieved with the aid of lithographically patterned nano-dimensioned oxide layers.

All-Dielectric Phase-Change Nanoantennae and Metasurfaces in Mid IR

4.07

M. Y. Shalaginov, Y. Zhang, S. An, P. Su, A. Agarwal, H. Zhang, T. Gu, J. Hu

Sponsorship: DARPA Extreme Optics and Imaging (EXTREME) Program



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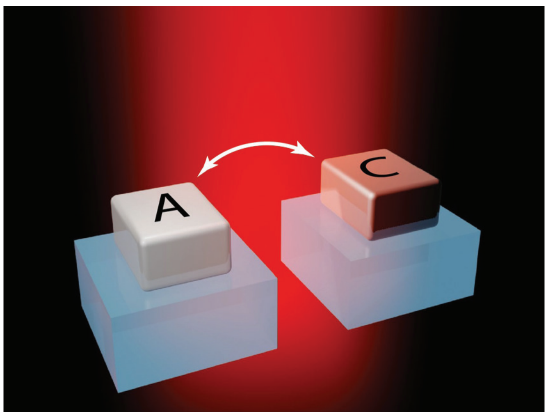
Available from August 2019.

Research Interests:
Photonic Materials, Nanophotonics, Quantum Optics

Sub-wavelength antennae are a fundamental building block for a plethora of imaging, sensing, and photodetection devices. Material platform based on chalcogenide glasses, such as recently emerged $Ge_2Sb_2Se_4Te_1$ (GSST), can open up new functionalities for sub-wavelength antenna engineering. GSST possesses unique optical properties, including high refractive index (3.2 - 5), low losses and phase-change ability in mid-IR (3-10um). Under certain conditions its crystal structure can switch between crystalline and amorphous states, which results in a significant change in the refractive index ($\Delta n>1$). Based on this material platform, we demonstrate all-dielectric nanoantennae with reconfigurable properties depending on the interplay between electrical and magnetic dipole resonances. This research opens up opportunities for further developments of ultrathin optical devices (metasurfaces) with tunable phase and amplitude switching.



◄ Figure 1. Illustration of a chalcogenide-glass-based nanoantenna, which can switch its optical response due to material transitioning from amorphous (A) to crystalline (C) state.

Self-Aligned Local Electrolyte Gating of 2D Materials with Nanoscale Resolution

4.08

C. Peng, D. K. Efetov, S. Nanot, R.-J. Shiue, G. Grosso, Y. Yang, M. Hempel, P. Jarillo-Herrero, J. Kong, F. Koppens, D. Englund

Sponsorship: Office of Naval Research, U.S. Department of Energy EFRC

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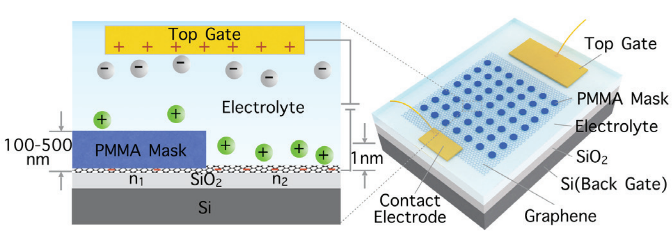
Available from June 2019.

Research Interests:
Optics, optoelectronics, nanotechnology, 2D materials, communication, imaging, sensing.

A central challenge in making 2D material-based devices faster, smaller, and more efficient is to control their charge carrier density at the nanometer scale. Traditional gating techniques based on capacitive coupling through a gate dielectric cannot generate strong electric fields at this scale due to fabrication constraints, precluding certain device concepts. Here we present a new gating concept based on a dielectric-free self-aligned electrolyte technique that allows spatially modulating charges with nanometer resolution. We employ a combination of a solid-polymer electrolyte gate and an ion-impenetrable e-beam-defined cross-linked PMMA mask to locally create excess charges on top of the gated surface. We prove the mask's ion-impenetrability and demonstrate its e-beam patterning down to 30 nm half-pitch resolution. We apply this technique to graphene and demonstrate the creation of tunable p-n junctions for optoelectronic applications. We also demonstrate the spatial versatility properties of this technique by introducing a novel graphene thermopile photodetector.



◄ Figure 1: Geometry and working principle of nanoscale electrolytic doping of 2D materials with a cross-linked PMMA screening mask.

4.09

Electric-Field-Induced Second-Order Nonlinearity in Silicon Waveguides

E. Timurdogan, C. V. Poulton, M. J. Byrd, M. Raval, M. R. Watts

Sponsorship: DARPA E-PHI, DODOS

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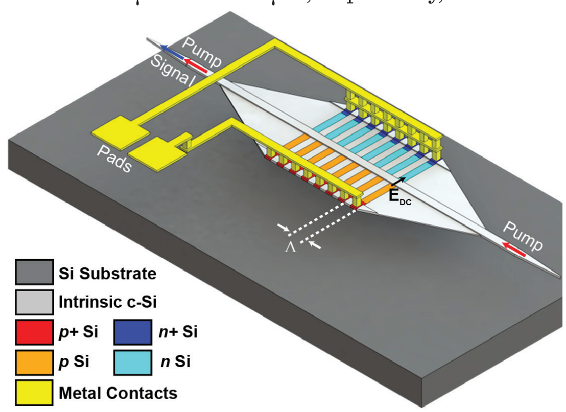
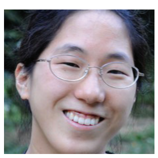
Available from June 2020.

Research Interests:
Silicon photonics, nonlinear Optics

Materials used in complementary-metal-oxide-semiconductor-compatible (CMOS-compatible) integrated photonic platforms (i.e. Si, SiN, Ge, and SiO_2) are centro-symmetric and therefore do not exhibit any significant second order nonlinear susceptibility, $\chi^{(2)}$. Recently, we demonstrated that an effective $\chi^{(2)}$ may be induced in silicon by applying a direct current (DC) field across a ridge waveguide by means of a reverse biased p-i-n junction. Inversion symmetry is perturbed because the dipole moments reorient to align with the applied DC field. This process converts silicon's large $\chi^{(3)}$ into an effective $\chi^{(2)}$, thereby enabling processes such as second harmonic generation (SHG), sum frequency generation (SFG), difference frequency generation (DFG), and phase-only modulation. First, we use this field-induced $\chi^{(2)}$ to demonstrate phase-only modulation using the DC Kerr effect. Second, we periodically pattern the p-i-n junction to quasi-phase-match pump and signal waves at 2.29 μm and 1.145 μm, respectively, to realize SHG with an efficiency of 13±0.5% W^{-1}.



◄ Three-dimensional sketch of the electric-field-induced second harmonic generation (EFISHG) device with the silicon ridge waveguide and periodic patterning of the p-i-n junction for quasi-phase-matching. Dimensions are not to scale.



4.10

Critical Design Parameters for Omnidirectional 2D Filled Photonic Crystal Selective Emitter for Thermophotovoltaics

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

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

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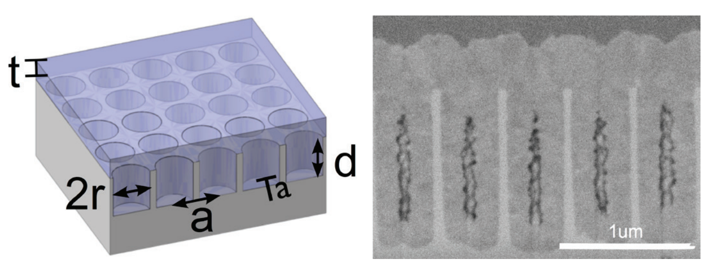
Available from June 2019.

Research Interests:
Photonics, optoelectronics, nanomaterials, nanotechnology

Thermophotovoltaic (TPV) systems are promising as small scale, portable generators to power sensors, small robotic platforms, and portable computational and communication equipment. In TPV systems, an emitter at high temperature emits radiation that is then converted to electricity by a low bandgap photovoltaic cell. One approach to improve the efficiency is to use hafnia-filled two-dimensional (2D) tantalum (Ta) photonic crystals (PhCs). These emitters enable efficient spectral tailoring of thermal radiation for a wide range of incidence angles. However, fabricating these PhCs is difficult. We use focused ion beam (FIB) imaging and simulations to investigate the effects of fabrication imperfections on the emittance of a fabricated hafnia-filled PhC and to identify design parameters critical to the overall PhC performance. We demonstrate that, more so than uniform cavity filling, the PhC performance relies on the precise cavity period and radius values and thickness of the top hafnia layer.



◄ Left: Schematic of a filled photonic crystal (PhC). The geometric parameters are cavity period a, cavity radius r, cavity depth d, and hafnia thickness t. The substrate is tantalum. Right: Focused ion beam (FIB) image of the fabricated filled PhC cross section clearly shows incomplete cavity filling and a thick layer of hafnia above the cavity.

Quasi-Bessel-Beam Generation using Integrated Optical Phased Arrays

4.11

J. Notaros, C. V. Poulton, M. J. Byrd, M. Raval, M. R. Watts

Sponsorship: DARPA E-PHI Program, National Science Foundation GRFP

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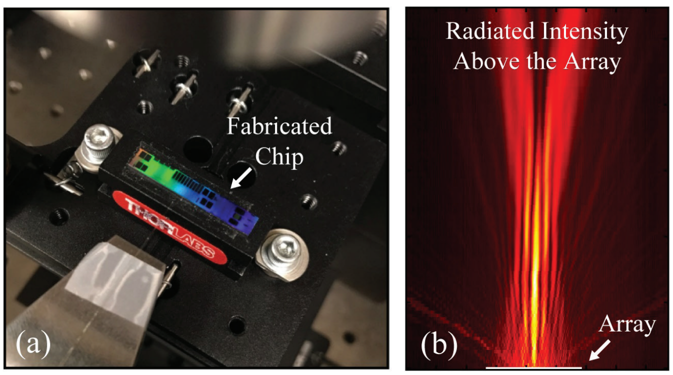
PhD advised by Michael Watts.

Research Interests:
Silicon photonics, optical phased arrays, integrated optics.

Due to their unique diffractive and reformative properties, Bessel beams have contributed to a variety of important advances and applications, including multiplane optical trapping, reduced scattering and increased depth of field microscopy, improved laser corneal surgery, and adaptive free-space communications. Recent work has turned toward generation of Bessel beams using compact form factors, including spatial light modulators, Dammann gratings, and metasurfaces. However, these demonstrations do not provide full on-chip integration, and most are fundamentally limited to static beam formation.

In this work, integrated optical phased arrays, which manipulate and dynamically steer light, are proposed and demonstrated for the first time as a method for generating quasi-Bessel beams in a fully integrated, compact-form-factor system. A new Bessel-Gauss theoretical framework and CMOS-compatible phased-array architecture are developed and utilized to demonstrate a 0.64mm × 0.65mm aperture integrated phased array, which generates a quasi-one-dimensional Bessel-Gauss beam with a ~14mm Bessel length and ~30μm FWHM.



◀ Figure 1: (a) Photograph of a fabricated integrated optical phased array chip. (b) Measured intensity above the quasi-Bessel-beam-generating phased array.

Network of OPOs as an Ising Solver and D-Wave Comparison

4.12

R. Hamerly, E. Rieffel, Y. Yamamoto, D. Englund

Sponsorship: JST ImPACT Program, ORISE IC Postdoctoral Fellowship

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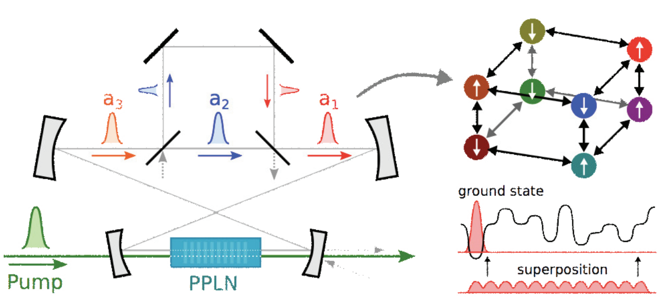
Postdoctoral Associate supervised by Dirk Englund.

Research Interests:
Photonics, nonlinear optics, neuromorphic computing, quantum information.

We construct an optical "Ising machine" using a nonlinear cavity pumped by a train of pulses, which functions as N independent optical parametric oscillators. Each oscillator acts as a spin in an Ising network, and we use an FPGA measurement-feedback system to realize the couplings. The Ising machine is designed to transition from an equal superposition of all states below the lasing threshold to the Ising ground state above threshold, providing a route to solve NP-hard Ising problems. In practice the machine does not always reach the ground state with 100% probability, so we perform benchmarking studies against classical and quantum Ising solvers, including the D-Wave 2000Q system at NASA Ames. For sparsely-connected problems (e.g. Max-Cut on cubic graphs), the Ising machine's performance is comparatively poor, but it does significantly better for dense problems. We believe that developing this device in integrated photonics may lead to further performance improvements.



◀ Figure 1: A synchronously-pumped OPO creates a train of pulses inside the cavity, which are used as spins in an Ising network, which transitions from a superposition of states below threshold to the Ising ground state above threshold.

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Available from April 2019.

Research Interests:
Quantum Computing, Silicon Photonics, Nanophotonics

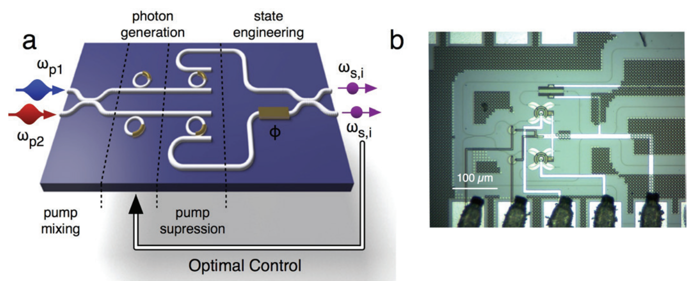
Classical Optimal Control for Photonic Quantum Computing

4.13

J. Carolan, N. Harris, M. Pant, T. Baehr-Jones, M. Hochberg, D. Englund

Sponsorship: Marie Skłodowska-Curie Global Fellowship

Quantum computing architectures necessitate exquisite control over a large number of individual quantum systems. Typically, such systems are incredibly sensitive to environmental fluctuations, and diagnosing errors via measurements causes unavoidable perturbations. Photonic quantum computers are uniquely situated where much of the monitoring and error diagnosis can be done via classical fields and measurement apparatus, with an intrinsically high signal-to-noise ratio. Using newly developed optimal control techniques, we demonstrate high-fidelity operation of a silicon photonic circuit, which generates photons via the nonlinear four-wave mixing effect. Through these techniques we demonstrate record photon generation rates, high-visibility quantum interference and robustness in the presence of environmental noise. These techniques will be indispensable as photonic quantum systems are scaled up, and may also find application in other qubit systems which exhibit classical proxies for quantum information.



◄ A Silicon photon source based on four wave mixing. (a) A schematic demonstrating pump routing, photon generation, filtering and state engineering. (b) Optical micrograph.

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SM advised by Brian Anthony.
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Research Interests:
Manufacturing, nanofabrication, process control, sensors

Setting Up and Operating an Education Packaging Factory – Developing Integrated Photonics Packaging Process

4.14

M. Sun, K. Zheng, A. Agarwal, B. Anthony

Sponsorship: AIM Photonics, US. Department of Defense

Device packaging is one area that is not heavily researched in academia. Research groups often outsource their packaging tasks to OEMs (original equipment manufacturers), and they are time and cost ineffective. Our group is setting up the MIT-LEAP (Laboratory for Experiment And Prototyping) that aims to scale up integrated photonics device packaging to a thousand pieces. The factory space will be 1) integrated in the academic environment, 2) produce equipment or components for education, research, and early production needs and 3) serve as a laboratory-factory to teach advanced manufacturing and integrated photonics concepts to students and engineers from industry. With this factory, we can bridge the gap between research groups and major manufacturers.

Currently, we are working on designing and packaging our first pilot products – a light sensor. It consists of components such as laser chips, submounts, laser drivers on the transmitter side, and photo detectors on the receiver side.

◄ Figure 1: The main equipment in the factory are listed in the figure. A: die bonder. B: X-ray inspection machine. C: wire bonder. D: reflow oven. E: microscope. F: Plasma cleaner.

Silicon Photonics Process Variability Modelling

4.15

S. I. El-Henawy, D. S. Boning

Sponsorship: AIM Photonics

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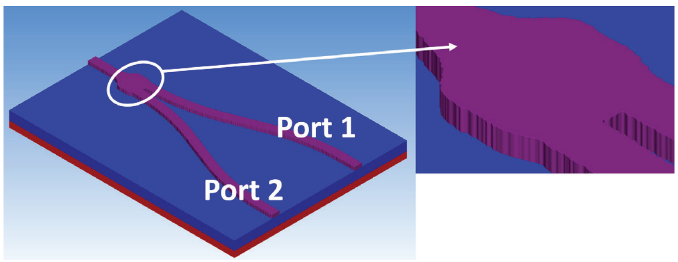
Research Interests:
Silicon photonics, modelling, electromagnetics.

With the rising demand for silicon photonics as a design platform in many applications, it becomes crucial to facilitate the photonic design flow by providing Process Design Kits (PDKs) that are compatible with existing CMOS fabrication infrastructure. A step for this is to extend PDKs to include photonic process variability models that are aware of the variations occurring during fabrication process.

We present a study for the impact of a random process variation, line edge roughness (LER), on fundamental component, the Y-Splitter. It is supposed to transmit the input power equally between its two output ports; however, an interesting imbalanced transmission is observed due to LER, depending on the statistical nature (amplitude and correlation length) of LER. The analysis of this process variation, and others, will help in developing a variation-aware model that will enable designers to predict and optimize behavior, performance, and yield of complex silicon photonic circuits.



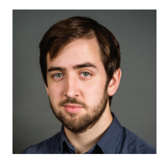
◄ Figure 1: Y-Splitter with emulated line edge roughness added, which results during the lithography step in manufacturing.

Low-Loss Waveguides in the Blue and Ultraviolet Spectrum using ALD Al_2O_3

4.16

G. N. West, K. K. Mehta, R. J. Ram

Sponsorship: NSF, MIT Lincoln Lab



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Available from August 2022.

Research Interests:
Optical sources, nanophotonics, UV sensing, quantum information processing.

Since its inception two decades ago, the field of integrated photonics has enjoyed considerable success using silicon for creating nanophotonic structures. The combination of well-developed fabrication techniques and low intrinsic loss in the infrared encourages use of silicon nanophotonics to replace a variety of traditional technologies in data communication, sensing, and imaging. Silicon's bandgap at 1.1μm does, however, limit its use for devices in the visible and ultraviolet – which encompasses a large set of problems such as augmented reality, optogenetics, enhanced biosensing, and quantum computing. Other common materials such as silicon nitride and the III-V cubic semiconductors have similar drawbacks, to greater or lesser extents.

Our alternative is amorphous aluminum oxide (alumina), cousin to the crystalline sapphire, deposited by atomic layer deposition. Like sapphire, alumina has excellent transparency into the ultraviolet with the high optical damage resistance necessary for the intense fields produced by nanophotonic structures. Also like sapphire, alumina is very difficult to etch – RIE chemistries are slow and typically produce sloped, rough sidewalls. We discuss the etching of alumina with methods that produce smooth, high-angle sidewalls. The first example of confined, low-loss single-mode waveguides in the ultraviolet regime are demonstrated. Vertical grating couplers operating at 405 nm and 379 nm are used to couple light into and out of waveguides with bends, splitters, and resonators.

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Research Interests:
Energy, nanomaterials, optoelectronics, photovoltaics.

The Role of Air Exposure in Improving Performance of PbS Quantum Dot Solar Cells

5.01

M. Sponseller, J. Jean, A. Osherov, M. Bawendi, V. Bulović
Sponsorship: Tata-MIT GridEdge Solar

Lead sulfide (PbS) quantum dots (QDs) are attractive solar materials due to their strong, broadband absorption, tunable electronic properties, and compatibility with low-temperature, solution-based deposition methods. State-of-the-art QD solar cells have reached power conversion efficiencies beyond 8% with air storage stability greater than 100 days, attributed to innovations in ligand treatments and architectural improvements. Several studies on QD solar cells employing a tetrabutylammonium iodide-treated PbS QD absorber layer along with a thin ethanedithiol-treated PbS QD hole transport layer and gold anode have shown substantial efficiency improvements (up to 50% or greater) when fully-fabricated devices are aged in air over days, but the nature and mechanism of this improvement remain unexplained.

Here, we systematically characterize the effect of varying degrees of air exposure on device performance through time-dependent, environment-controlled current-voltage measurements. We find that aging QD films before electrode deposition and full devices after electrode deposition both improve device performance compared to films and devices aged under inert conditions but to different degrees, suggesting multiple air exposure effects are occurring on different timescales. We investigate the origin of these improvements in device performance using photoelectron spectroscopy and optical measurements on films and full devices.

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Available from June 2022.

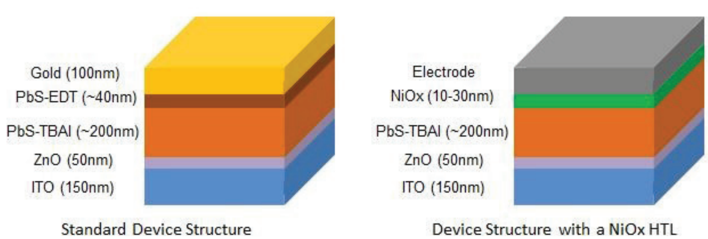
Research Interests:
2D materials, energy, nanomaterials, optoelectronics, photovoltaics.

Nickel Oxide as a Hole Transport Layer in Lead Sulfide Quantum Dot Solar Cells

5.02

E. Wassweiler, M. Sponseller, J. Jean, A. Osherov, M. Bawendi, V. Bulović
Sponsorship: Tata-MIT GridEdge Solar

The versatile characteristics of lead sulfide quantum dots (PbS QD) makes them an attractive material to develop high efficiency, low cost, and flexible photovoltaics (PVs). Hole transport layers (HTL) and electron transport layers are essential building blocks in these solar cell architectures. PbS QDs with an EDT ligand are widely used as an HTL in the high-efficiency QDPVs. However, limited compatibility of the EDT with different electrode materials urges the need for the development of a new HTL to use with materials currently incompatible with the EDT ligand. High work function and large band gap make nickel oxide (NiOx) an attractive alternative HTL for QDPVs. Herein we demonstrate the functionality of NiOx as a buffer layer to allow utilization of other electrode materials and the potential of NiOx to become the only HTL in a high performance QDPV.



◄ Comparison between standard device structure and a device structure incorporating a NiOx HTL.

The Uncommon Nature of Point Defects in Organic-Inorganic Perovskite Solar Cells

5.03

O. Hentz, Z. Zhao, P. Rekemeyer, A. Singh, S. Gradečak

Sponsorship: Eni S.p.A

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PhD advised by Silvija Gradečak.
Available from June 2018.

Research Interests:
Organic-inorganic perovskite solar cells, defect migration, electron microscopy techniques.

Organic-inorganic perovskite solar cells (PSCs) have shown enormous success in the past decade, increasing in power conversion efficiency from ~4% in 2009 to >22%. One of the critical properties that has been attributed to this success is "defect tolerance": in organic-inorganic perovskites, the majority of point defects with low formation energy lie within or near the conduction or valance band. We demonstrate that, despite the preference for shallow defects, point defects play an integral role in materials properties and PSC device performance.

We first study the role of point defects on nanoscale luminescence properties of inorganic-organic perovskites by using cathodoluminescence in scanning transmission electron microscope (STEM). By correlating local luminescence properties with compositional variations using STEM, we demonstrate that iodide segregation induced by the electron beam is correlated with a device-relevant spatially-localized high-energy emission. Next, we study the effects of directional point defect segregation under an applied electric field on current extraction from PSCs. Specifically, we use electron beam induced current measurements in a scanning electron microscope to measure the inhomogeneity in current extraction before and after forward biasing the device. These measurements point to preferential defect migration at extended defects and allow us to identify low frequency capacitive elements related to compensation of charged defect segregation under applied biasing. Finally, we directly track the migration of deep defects in PSCs through PL mapping of laterally biased perovskite films. Using Monte Carlo simulations of defect drift and diffusion to model these time dependent luminescence maps, we provide information about the nature of deep trap states in these materials. Our work demonstrates the ways in which deep and shallow defects play a critical role in PSCs and suggests that the ultimate stability and performance of PSCs will be dependent on either reducing point defect concentrations or inhibiting defect migration.

Adsorbed Metal Cations Stabilizing the Surfaces of Perovskite Oxide Cathode Materials

5.04

R. Bliem, D. Kim, B. Yildiz

Sponsorship: Air Force Office of Scientific Research, Austrian Science Fund FWF

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Available from July 2019.

Research Interests:
Oxide surfaces, Energy conversion, Information storage, Solid oxide fuel cells.

Highly active doped ternary oxides, including perovskites, are common functional materials in energy conversion, catalysis, and information processing applications. At elevated temperatures related to synthesis or operation, however, surface segregation of dopant cations is a common problem of state-of-the-art materials, such as the Sr-doped La-based transition metal perovskites $(La,Sr)CoO_3$, $(La,Sr)FeO_3$ (LSF), and $(La,Sr)MnO_3$ (LSM), used for example as solid oxide fuel cell cathodes. Sr segregation, driven by strain and electrostatics, leads to the formation of an inactive surface oxide, blocking the oxygen reduction reaction.

The deposition of metals with low reducibility (Zr, Ti, Hf) has been proposed to minimize the surface oxygen vacancy concentration, thus stabilizing the surface by reducing the electrostatic driving force. This approach has proven successful in stabilizing the surface of $La_{0.8}Sr_{0.2}CoO_3$ (LSC) thin films.

Here I investigate the relation between surface properties and the stability of electrochemical performance under the influence of deposited metal species. The goal is to achieve an in-depth understanding of the surface modifications underlying the enhanced surface stability observed for LSC. In parallel, I demonstrate the broad applicability of the effects of metal deposition by including LSM, an intrinsically different type of cathode material.

Using in-situ x-ray photoelectron spectroscopy (XPS) at high temperatures and oxygen pressures close to operating conditions and scanning probe microscopy, I compare the properties of LSM surfaces with and without prior deposition of metals. Depositing Hf on one half of LSM thin-films allows us to demonstrate an enhanced surface stability of the region modified by Hf compared to pristine LSM on the same sample.

Moreover, we investigate the effect of modifying the surface oxygen vacancy concentration by applying a bias voltage to the surface to confirm the close relation between surface oxygen vacancies and Sr segregation. This study is an important step to establish metal deposition as a strategy to enhance the surface stability of energy materials under operating conditions.

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Available from August 2022.

Research Interests:
Oxide thin films, electronic materials, energy conversion, perovskite oxides.

Effects of Electrochemical Potential on Aliovalent Dopant Segregation on Perovskite Oxides

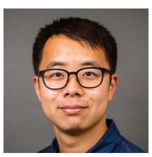
5.05

D. Kim, R. Bliem, G. Vardar, W. Bowman, B. Yildiz

Sponsorship: US Airforce Office of Scientific Research

La-based perovskite oxides such as $(La,Sr)MnO_3$ (LSM) have been extensively studied as functional materials in electronic and energy conversion devices. As cathodes in solid oxide fuel cells (SOFCs), they have high oxygen reduction activity and good compatibility with electrolyte material. However, the activity for oxygen reduction and incorporation is hampered by the surface segregation of aliovalent dopants such as Sr. This dopant segregation to the oxide surface often leads to the formation of insulating phases that hinder the catalytic reaction. This interface chemical degradation is equally important for the use of these materials in electronic devices since the interface charge transfer properties are also degraded.

The present study systematically investigates the effect of polarization on dopant segregation with surface-sensitive analytical techniques. A potential gradient parallel to the surface of LSM thin-film model cathodes is applied, following a design by Huber et al (*Journal of the Electrochemical Society*, 164 (2017) F809-F814). Thus, the effective oxygen chemical potential, μO_2, is changed across the surface, which modifies the local oxygen vacancy concentration and therefore affects the electrostatic driving force of segregation. The cation composition was measured at five points with different effective μO2 by ambient pressure X-ray photoelectron spectroscopy (APXPS). The amount of segregated Sr was calculated by deconvoluting the Sr 3d peak into two doublet components: a surface component and a lattice component, corresponding to Sr in the surface species and in the original perovskite phase, respectively. We observed a clear trend towards stronger segregation as cathodic polarization was increased across the surface. The studied potential ranged from 0 mV to -500 mV. Furthermore, a significant change to the resonant photoemission spectra of Mn indicated segregation of Sr under polarization, following the potential gradient. These results indicate that cathodic potential promotes segregation of Sr out of perovskite lattice.



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Research Interests:
Oxide surfaces, Energy conversion, Heterogeneous Catalysis.

Uncovering Biaxial Strain Effect on Reducibility and Exsolution Kinetics for Thin-Film Perovskites

5.06

J. Wang, A. K. Opitz, B. Yildiz

Sponsorship: Exelon Corporation

Exsolution of metallic particles from an oxide matrix is a promising approach to generate catalytically highly active nanoparticles with both high stability and activity. However, this method has thus far been solely empirically developed, without a clear understanding of the fundamental mechanisms to optimize the resulting catalysts (e.g., the exsolution rate, the dispersion and composition of exsolved particles, interaction of the particles with the supporting oxide).

Our recent results indicate that in-plane biaxial strain can be a powerful tool in affecting the exsolution process while the fundamental mechanism has yet remained unclear. Herein I report our recent findings on how biaxial strain affects the exsolution of reducible transition metals from perovskite-type oxides. We use ambient pressure X-ray spectroscopy to probe defect chemistry, surface composition, and exsolution rate on perovskite-type thin-film samples. In particular, we will quantify the strain effect on the materials' reducibility (i.e., thermodynamic driving force needed to achieve exsolution), and on cations' mobility (i.e., exsolution kinetics). The insights provided in this study enable a precise control over the exsolved nanoparticles and therefore lead to an enhanced performance of catalysts, especially for clean energy technologies.

Interface Chemistry of Solid Electrolyte/Electrode Interfaces Probed by X-Ray Spectroscopy

5.07

G. Vardar, Y. M. Chiang, B. Yildiz

Sponsorship: Bosch Energy Research Network, MIT Energy Initiative

Solid-state lithium-ion batteries (SLIBs) hold great promise for obtaining higher energy densities but the power density is currently limited by the electrode-electrolyte interfaces. The high resistances at SLIB interfaces are hypothesized to be due to chemical mixing, space charge formation, or secondary phase formation. Although several secondary phases have been proposed theoretically, there is the need for a systematic experimental work studying the secondary phase formation as a function of temperature and applied voltage. Extended X-ray absorption fine structure spectroscopy (EXAFS) is a unique capability that allows us to probe the fine structure around the atoms at the electrode-electrolyte interface and their oxidation states. Depth-sensitive X-ray absorption spectroscopy allows us to probe the changes in structure at the interface even if the secondary phases are not crystalline. In this work I focus on the interface between lithium lanthanum zirconium oxide (LLZO) and lithium cobalt oxide (LCO) sputtered thin films. Current results indicate a temperature induced formation secondary phases at this interface, initiating as low as at 300C. Correlations between the chemistry of those interfaces and the electrochemical charge transfer are established.

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Research Interests:
Batteries, electrochemistry, spectroscopy.

Modeling Microstructures in Lithium Battery Electrodes

5.08

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Sponsorship: US Department of Energy, Lindemann Fellowship

Current continuum models for phase transition in electrode materials typically average the effects of microscopic configurations, such as lattice orientations, distortions, and the presence of defects. Consequently, the effects of individual atomic arrangements on the electrochemical cycle are not explored. To overcome these limitations, we develop and apply a coupled 2D Cahn-Hilliard – phase field crystal (CH-PFC) model to describe phase transition in a LiFePO4 electrode material. The CH-PFC model couples the lithium ion composition field with the lattice symmetry of the LiFePO4 electrode material. We use this coupled approach to explore 2D lattice arrangements in a LiFePO4 electrode as a function of the composition field.

The simulation reveals presence of multiple grains in a single FePO4/ LiFePO4 phase and identifies the position and orientation of grain boundaries. We next identify local lattice distortions across phase boundaries. We track the migration of grain boundaries during an electrochemical cycle in the electrode model system. The simulations demonstrate that lattice defects disappear and crystallinity of the nanoparticle electrode increases after one electrochemical cycle. Furthermore, fine twins are observed to form in the electrode microstructure to elastically relax the lattice misfits. To sum up, the study provides insights into the lattice arrangements in electrode microstructures and describes the structural evolution of lattices during FePO4 / LiFePO4 phase transition.

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Available from October 2018.

Research Interests: Theoretical and computational modeling, microstructures, ferroelectrics, lithium batteries.

Energy Harvesting Footwear

5.09

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Sponsorship: MIT–SUTD International Design Center

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Available from June 2018.

Research Interests:
MEMS product design, energy harvesting, self-powered sensors

Most portable electronic devices are power-limited by battery capacity, and recharging these batteries often interrupts the user's experience with the device. The product we presented in this paper provides an alternative to powering portables by converting regular human walking motion to electricity. The design harvests electric power using air bulbs, distributed in the sole of a running shoe to drive a series of micro-turbines connected to small DC motors. The number and position of air bulbs is optimized to harvest the maximum airflow from each foot-strike. The system is designed to continuously turn the micro-turbines by utilizing both outflow and inflow from the air bulbs. A prototype boot was outfitted with the energy harvesting system, and produced average continuous power on the order of 10s of mW during walking at 3.0 mph, used to power a passive GPS tracker which periodically relayed geographical coordinates to a smartphone.

◂ Combat boot fitted with energy harvesting pump system and GPS receiver.

Low-Frequency, Low-Amplitude MEMS Vibration Energy Harvesting

5.10

R. Xu, H. Akay, S.-G. Kim

Sponsorship: MIT-SUTD International Design Center

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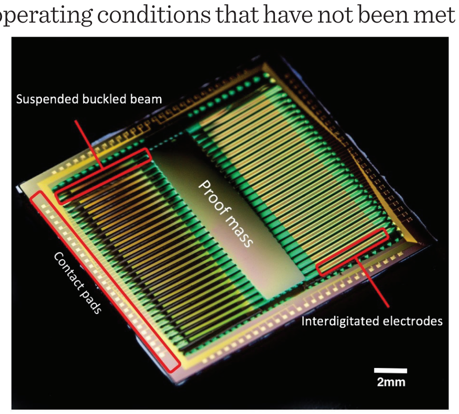
Available from February 2018.

Research Interests:
MEMS, energy harvesting, transducers.

Vibration energy harvesters work effectively only when the operating conditions match the available vibration source. Typical resonating MEMS structures cannot be used with the low-frequency, low-amplitude and unpredictable nature of ambient vibrations. Bi-stable, non-linear oscillator-based energy harvesters are developed for lowering the operating frequency while increasing the bandwidth, and are realized at MEMS scale for the first time. This design does not rely on the resonance of the MEMS structure but operates with the large snapping motion of the beam at very low frequencies. A fully functional piezoelectric MEMS energy harvester is designed, monolithically fabricated and tested. Residual stress induced buckling is achieved through the progressive control of the deposition along the fabrication steps. Dynamic testing demonstrates the energy harvester operates with 50% bandwidth between 30Hz and 70Hz at 0.5g, operating conditions that have not been met before by MEMS vibration energy harvesters.



◂ Buckled beam based MEMS vibration energy harvester

Large Scale Broadband Acoustic Energy Harvesting via Synthesized Negative Impedance

5.11

N. Monroe, J. H. Lang

Sponsorship: Ferrovial, S.A.

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PhD advised by Jeffrey Lang and Anantha Chandrakasan.
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Research Interests:
Energy harvesting, acoustics, audio electronics, power electronics.

With the rise of IoT and connected devices, the need for self-powered wireless sensor nodes is ever increasing. One promising technology for self-powered sensor nodes in noisy environments is acoustic energy harvesting: deriving energy from ambient sound. Current acoustic energy harvester designs are typically based on resonant structures, yielding narrowband energy collection and therefore low energy collection from broadband noise sources. In addition, current acoustic energy harvesters tend to exhibit MEMS-scale sizes (square microns), consequently with low power outputs.

This work aims to improve the size and bandwidth of such harvesters. A large-scale acoustic energy harvester is proposed, based on piezoelectric PVDF (Polyvinylidene Fluoride) film tens of square centimeters in size. A light vacuum behind the film provides a DC bias point in deflection, improving performance and effectively linearizing the system. An energy-based dynamics analysis of such a system driven by an acoustic source yields a third-order nonlinear differential equation, representing the electromechanical dynamics of the system in open-circuit state.

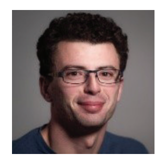
The dynamics of the system can be represented by an equivalent RLC circuit model and subsequently a Thévenin equivalent model, looking into the piezoelectric element's terminals. Optimal broadband energy harvesting is achieved with a conjugate matched load at all frequencies. Such a load is simplified and realized over the desired frequency range as a series combination of a resistance and negative capacitance. We realize this load initially using operational amplifier circuits, and in future iterations losslessly using switched power electronics techniques. Essentially reactive power is invested in exchange for an increase in real power. A successful result could pave the path towards acoustically-powered sensor nodes, especially in the case of broadband noisy environments such as airports and highways. It also has potential applications in noise abatement.

Crystallization during Boiling: Fundamentals to Mitigation

5.12

S. Dash, L. Rapoport, K. K. Varanasi

Sponsorship: Chevron Corporation



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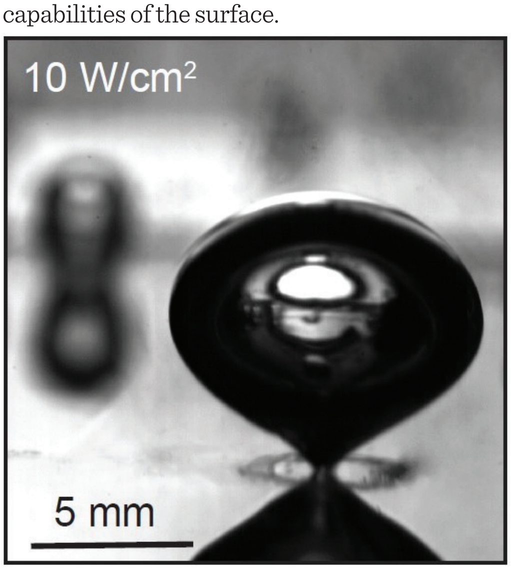
Available from June 2018.

Research Interests:
Heat transfer, fluid mechanics, interfacial phenomena.

Scale formation due to the presence of dissolved salts poses serious problems to a variety of industries including desalination, and oil and gas. In particular, salts with inverse solubility with temperature adhere to the heat transfer surface and adversely affect the thermal transport. In this study, we show that these salts can reduce the critical heat flux (CHF) up to three times from its initial values even when the solution is undersaturated. We use simultaneous high speed and infrared imaging to understand the interdependence between crystallization and bubble dynamics, and propose a passive way to mitigate deposition and restore the heat transfer capabilities of the surface.



◀ Bubble generated in an undersaturated salt solution leaves a ring shaped scale deposit.

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Available from June 2020.

Research Interests:
Electron microscopy, electron optics.

Ptychographic Electron Beam Imaging

6.01

A. Agarwal, H. Iglesias, C.-S. Kim, K. K. Berggren
Sponsorship: Gordon and Betty Moore Foundation

Quantum electron microscopy (QEM) has recently been proposed as a method for high-resolution imaging of radiation-sensitive samples, such as proteins and biomolecules. QEM uses electron interference in a resonator to image the sample. The resonator design requires very low-aberration beams to ensure high imaging resolution. However, electron lenses in conventional microscopes have high spherical and chromatic aberration coefficients. This is especially problematic in a resonator, where electrons pass through these lenses several times and aberrations build up with each pass. We are exploring ptychographic electron imaging as an alternative to conventional imaging. This technique avoids lens aberrations by eliminating imaging lenses. The image of a sample is reconstructed from a series of diffraction patterns, recorded at different beam positions. Overlap between the illuminated areas on the sample at each beam position provides the required data redundancy to reconstruct the image of the sample. The ptychography algorithm (extended Ptychography Iterative Engine - ePIE) also reconstructs the imaging probe, and therefore can be used to characterize beam aberrations. We have implemented the technique numerically using a standard TEM image. We used an electron beam with energy 200 keV, coefficient of spherical aberration (Cs) 2 mm, and defocus 50 nm to generate the diffraction patterns in our simulation. We also extracted Cs and defocus from the reconstructed probe image. These extracted coefficients match those used to generate diffraction patterns quite well. We are now implementing ptychography in an existing transmission electron microscope to develop a robust experimental protocol. We will then use this protocol to characterize aberrations in a modified scanning electron microscope that we are using as a test-bed for QEM. We hope that this technique will serve as a general beam diagnostic tool.

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PhD Student advised by Pablo Jarillo-Herrero.
Available from September 2022.

Research Interests:
2D materials, graphene, superconductivity

Tunneling Spectroscopy of Graphene Nanodevices Coupled to Large Gap Superconductors

6.02

D. Rodan-Legrain, J. I-J. Wang, L. Bretheau, K. Watanabe, T. Taniguchi, P. Jarillo-Herrero
Sponsorship: La Caixa Fellowship, DOE, NSF, Moore Foundation

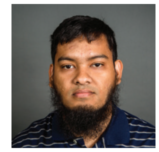
A normal conductor, when placed in close proximity between two superconductors, can inherit some of their properties and become itself superconducting. Microscopically, this phenomenon, known as proximity effect, is due to the formation in the conductor of electron-hole states, called Andreev states. Graphene can exhibit low contact resistance and weak scattering when connected to superconducting electrodes. These properties, together with its large mobility, ease of access and tunable density of states provide an interesting platform to study Andreev Physics in two dimensions. From the experimental point of view, the ability to produce and manipulate 2D materials, such as graphene and hBN, is a major improvement in condensed-matter physics. These isolated atomic planes can actually be reassembled into a designed heterostructure made layer by layer in a precisely chosen sequence, here engineered to perform spectroscopy through an ultrathin hBN tunneling barrier in a fully encapsulated graphene. With such technique, it is even possible to access electronic properties of the material of interest in the energy domain. We will thus present the fabrication process that allowed us to perform tunneling spectroscopy in normal and proximitized superconducting graphene in ballistic regime. Here, we performed tunneling spectroscopy measurements of graphene coupled to Nb/NbN superconducting electrodes. The measured energy spectra of graphene density of states, which depends on the phase difference between the superconductors, show the presence of a continuum of Andreev bound states and exhibit a hard induced gap. Thanks to our particular device structure and geometry, we were also able to measure the Andreev spectrum as a function of the graphene Fermi energy, showing a transition between different regimes. Furthermore, at energies larger than the superconducting gap, we observed phase-dependent energy levels displaying the Coulomb blockade effect, which are interpreted as arising from quantum dots coupled to the proximitized graphene.

High Performance Graphene-base Hot Electron Transistor with GaN Emitter

6.03

A. Zubair, A. Nourbakhsh, H. Wang, M. Qi (University of Notre Dame), M. Hempel, J. Kong, D. Jena (Cornell University), M. Dresselhaus, T. Palacios

Sponsorship: Army Research Office



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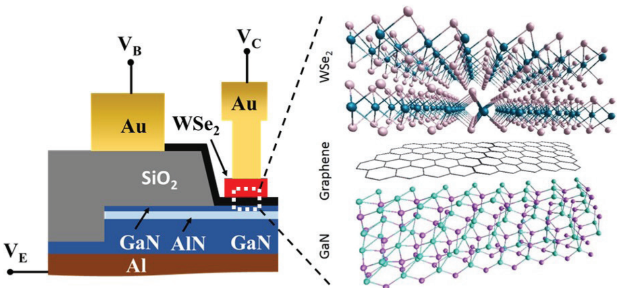
PhD advised by Tomás Palacios and Mildred Dresselhaus.
Available from June 2018.

Research Interests:
2D materials, electronic devices, energy harvesting devices and systems, GaN, nanomaterials, nanotechnology, optoelectronics, quantum devices.

Hot electron transistors (HETs) are promising devices for potential high-frequency operation and hot electron spectroscopy. In HET, carrier transport is due to the injection of hot electrons from an emitter to a collector which is modulated by a base electrode. Monolayer graphene, being the thinnest available conductive membrane in nature, provides us with the opportunity to study the HET transport properties at the ultimate scaling limit. Previously, we have demonstrated high performance graphene-base HET with GaN/AlN emitter and a graphene/WSe_2 van der Waals heterostructure collector base-collector stack. In this work, we discuss the effect of material parameters on the transport properties of the heterojunction diodes (i.e. Emitter-Base and Base-Collector) of HETs, and their impact on the HET performance. Temperature dependent transport measurements identify quantum mechanical tunneling as the major carrier transport mechanism in HETs. Finally, we demonstrate a new generation of graphene-base HET with record current density above kA/cm^2.



◄ Schematic cross-section of graphene-base hot electron transistor.

Building Microscopic Sensor Platforms out of Two-Dimensional Materials

6.04

M. Hempel, E. McVay, J. Kong, T. Palacios

Sponsorship: Air Force Office of Scientific Research (AFOSR)

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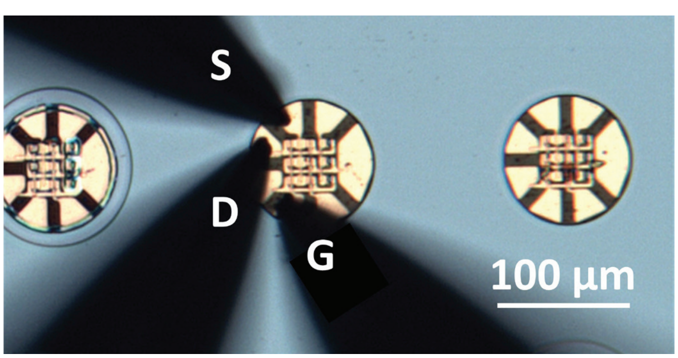
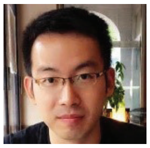
Research Interests:
2D materials, electronics, integrated circuits, nano-manufacturing, nanomaterials, nanotechnology.

Most sensors in use today have macroscopic dimensions. However, making sensors smaller than the diameter of a human hair could enable a new paradigm of sensing. For example, having sensors that are small and light enough to travel with the wind would open up new ways of environmental monitoring. To explore this new domain, we built a 100-µm-wide flexible polymer disk that has three chemical sensors and an identifier number in the form of read-only-memory transistors. The transistor channels and sensors are made of a single atomic layer of molybdenum disulfide (MoS2). This material is flexible and useful to build digital electronics and very sensitive sensors. So far, we have optimized the fabrication process and been able to demonstrate good transistor performance and response to chemical analytes. Furthermore, we developed a simple process to release these tiny systems from the silicon substrate by peeling them off with a water-soluble tap.



◄ Optical micrograph of three sensor systems on a silicon substrate. The middle one is being measured with probes to characterize the transistor performance.



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Available from June 2019.

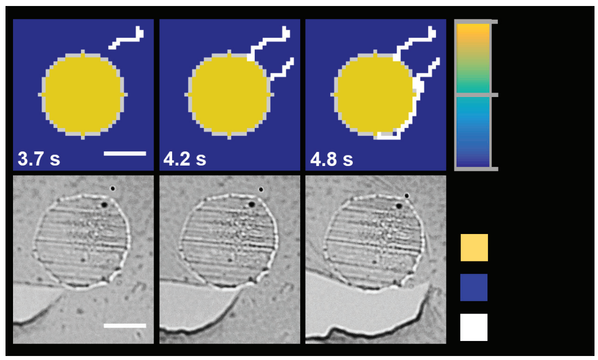
Research Interests:
The analysis and control of molecular conformation and engineering of low dimensional materials with applications in chemical transformation and energy generation.

Autoperforation of 2D Materials for Generating Two Terminal Memresistive Janus Particles

6.05

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: MURI

Due to its inherent stochasticity, brittle fracture is seldom used as a nanofabrication method. However, the imposition or templating of a specific strain field can guide fracture along a pre-set design. Herein, we show that this autoperforation provides a means of spontaneous assembly for 2D surfaces. Chemical vapor deposited mono- and bi-layer graphene, molybdenum disulfide (MoS2), or hexagonal boron nitride (hBN) autoperforate into circular envelopes when sandwiching a microprinted polymer spot, allowing lift-off and assembly into solution. The resulting composite microparticles have two independently addressable external Janus faces, and can function as an intraparticle array of parallel two terminal electronic devices. As an example, we print black phosphorous (BP) nanoflakes in polystyrene (PS) latex ink into monolayer graphene sandwich particles, resulting in micro-particles possessing non-volatile, 15 bit memory storage via a spatially addressable memresistor array throughout the particle interior. Such particles form the basis of devices capable of collecting and storing digital information in their environment.



◄ Comparison of simulated and experimental crack propagation during the autoperforation process

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Available from September 2020.

Research Interests:
2D materials, electronics, photonics.

Low-Temperature Copper Bonding Technology with Graphene Interlayer

6.06

H. Wang, W. S. Leong, F. Hu, L. Ju, C. Su, Y. Guo, J. Li, M. Li, A. Hu, J. Kong
Sponsorship: NSF, AFOSR FATE MURI

In this poster, we report a low bonding-temperature and highly-reliable Cu-bonding technology with the use of graphene as an interlayer. By integrating nanoscale graphene/Cu composite on the Cu substrate prior to thermocompression bonding, we observe a macro-scale phenomenon where reliable Sn-Cu joints can be fabricated at a bonding temperature as low as 150 °C, which is the lowest reported value to date for Cu bonding technology. Specifically, we electrochemically deposit a layer of Cu nanocone array on the Cu substrate and cover it with a graphene sheet, prior to the bonding process. When subjected to heat, microscale Sn solder deforms and replicates the Cu nanocone array morphology, and hence transforming into nanoscale Sn. Compared to microscale Sn, nanoscale Sn has much lower melting points and facile surface diffusion. This phenomenon effectively contributes to the low bonding temperature observed in our bonding technology. With the advancement in graphene synthesis and transfer technology, we believe the graphene-based Cu bonding technology presented in this work can be easily integrated into the existing commercial Cu bonding technology for industrial applications in the foreseeable near future, to greatly reduces the thermal budget required for electronics packaging.

Double Layers of Perforated Lamella Morphology from Si-Containing ABA Triblock Copolymer Self-Assembly

6.07

S. Lee, C. A. Ross

Sponsorship: NSF, CMSE, Kwanjeong Educational Foundation

Directed self-assembly (DSA) of block copolymer (BCP) films under solvent vapor annealing is an attractive method for fabricating highly ordered nanostructures with a variety of morphologies. There are many factors which determine the film morphology including film thickness, type of solvent and solvent vapor pressure. However, most studies use diblock copolymers and there is much less work on BCPs with more complex architectures due to the challenges associated with their synthesis. Compared to AB diblock copolymers, ABA triblock copolymers are attractive because they can more easily generate patterns such as perforated lamella and gyroid morphologies and they produce a smaller feature size for the same molecular weight. Here, we present a systematic study on the effect of film thickness and mixed solvent vapor ratio on the film morphologies of Poly(stryrene-b-dimethylsiloxane-b-styrene) (PS-b-PDMS-b-PS).

Combining experimental and self-consistent field theoretical approaches, phase behavior in thin films was described in detail as a function of as-cast film thickness and the flow rates of two different solvent vapors (toluene and heptane). In comparison with the case of diblock PS-b-PDMS, it was much easier to produce a highly ordered perforated lamella structure with a wider process window, and sub-15 nm features were made using triblock BCP which is smaller than that of a diblock BCP with same molecular weight. When the film comprised two layers of microdomains, a structure consisting of two layers of perforated lamella was produced, where the holes in one layer overlaid the junctions of the other, instead of the expected bulk gyroid morphology. We expect that this study will yield self-assembly principles to design a wide variety of nanostructures arising from ABA triblock copolymer self-assembly, and these materials can be broadly utilized in various applications such as templates, nanoporous membranes, and metamaterials.

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Research Interests:
2d materials, electronics, energy, molecular & polymeric materials, nanomanufacturing, nanomaterials, nanotechnology, organic materials

Photoluminescent Ultraviolet Curable Polymer-Quantum Dot Composite as Luminescent Down-Shifting Layer for Photovoltaics

6.08

G. Draaisma, A. Schenning, S. Meskers, C. Bastiaansen, D. Reardon

Sponsorship: DSM Advanced Solar

The efficiency of solar cells with a poor ultraviolet response can be improved by altering the incident light spectrum with luminescence down-shifting. Stable luminescent additives with a large Stokes shift, high photoluminescence quantum yield and a high absorption coefficient are required for this purpose. Quantum dots are attractive candidates which meet most of the basic requirements for luminescence down-shifting additives. Herein, commercially available heavy metal free core shell CuInS2/ZnS quantum dots are theoretically and experimentally evaluated as luminescence down-shifting additives. The small apolar dodecanethiol ligands of the quantum dots are exchanged with thiol functional oligo-caprolactone ligands, via a ligand exchange process, to improve the quantum dots compatibility with the ultraviolet curable resin matrix. Aggregation of the quantum dots is prevented to a large extent in the polymer–quantum dots composite films and the material exhibits luminescence properties which are virtually identical to the luminescence of the quantum dots dispersed in chloroform. Raman spectroscopy and NMR spectroscopy are used to elucidate the ligand exchange and ligand binding processes. It is shown that well-dispersed CuInS2/ZnS quantum dots are required with a near unity quantum yield to increase the efficiency of solar cells significantly especially if high performance inorganic solar cells are employed.

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Research Interests:
QD apps in PV, nanoparticle synthesis & colloid dispersions in printing apps, thin film processing.

Divya Panchanathan
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PhD advised by Gareth McKinley.
Available from June 2018.

Research Interests:
Interfacial phenomena, Wettability, Active surfaces, Photocatalysis.

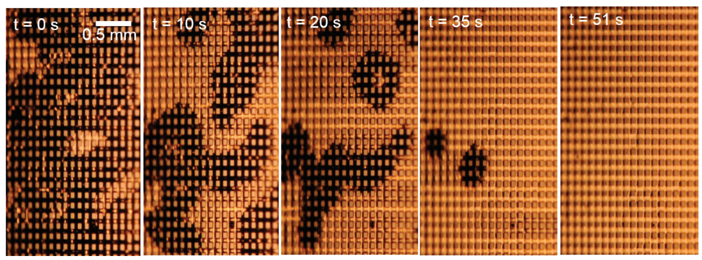
Gas Spreading on Superhydrophobic Surfaces Immersed Underwater

6.09

D. Panchanathan, A. Rajappan, K. K. Varanasi, G. H. McKinley

Sponsorship: King Fahd University of Petroleum and Minerals

Superhydrophobic surfaces submerged under water appear shiny due to a thin layer of air ('plastron') trapped in their surface texture. This entrapped air is advantageous for both anti-corrosion as well as frictional drag reduction in various applications ranging from microfluidic channels to marine vessels. However, these aerophilic textures are prone to impregnation by water due to turbulent pressure fluctuations and dissolution of the trapped gas into the water. We demonstrate a novel chemical method to replenish the plastron by using the decomposition reaction of hydrogen peroxide on a superhydrophobic silicon micro-post texture that incorporates a platinum catalyst. We also provide a thermodynamic framework for designing superhydrophobic surfaces with optimal texture and chemistry for underwater plastron regeneration. We finally demonstrate the practicability of this method by fabricating scalable surface textures on aluminum that incorporates a cheap catalyst, manganese dioxide, thus enabling plastron regeneration on larger length scales for ocean-going applications.



◄ Figure 1: In-situ gas generation and spreading on a superhydrophobic texture immersed in water. The texture is comprised of silicon micro-posts, platinum catalyst and TeflonTM.

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PhD advised by William Tisdale.
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Research Interests:
2D materials, nanomaterials, nanotechnology, optoelectronics

Synthesis and Photophysical Studies of 2D Lead Halide Perovskites for Optoelectronic Applications

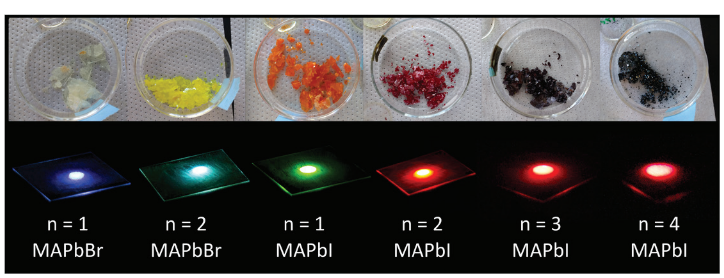
6.10

W. Paritmongkol, W. A. Tisdale

Sponsorship: Center for Excitonics

The approaching internet of things era, in which electronics will be embedded in all things around us, requires better materials with flexible form factors, easy fabrication, and excellent electronic properties. The emerging lead halide perovskites (LHPs) can satisfy these requirements due to their low-temperature solution synthesis, high optical absorption coefficients, and defect tolerance. Their properties are also tunable by changing their chemical composition, making them suitable for transistor, photodetector, and photovoltaic applications.

Adding ligands to a LHP synthesis results in 2D LHPs with high photoluminescence quantum yields. 2D LHPs exhibit quantum confinement; their properties depend on the 2D sheet thickness (n). Employing cooling-induced crystallization, we make 2D LHP single crystals with excellent thickness control for n = 1-4. The resulting crystals are stable and can be exfoliated into thin films, making them attractive for atomically-thin devices. We are studying carrier relaxation in these materials using photoluminescence and transient absorption spectroscopies.



◄ 2D single crystals of methylammonium lead bromide (MAPbBr) and methylammonium lead iodide (MAPbI) with various thicknesses (n) under ambient (top) and UV light illumination (bottom).

An Ultrasensitive Thermo-Mechanical Bolometer Based on Percolative Graphene Films

6.11

Y. Lin, X. Ji, E. N. Tas, H. Cheung, J. Kong, T. Palacios

Sponsorship: NSF CIQM, ARO MIT-ISN

Uncooled mid-infrared (Mid-IR) detection and imaging technologies are highly desired for night vision, security surveillance, remote sensing, industrial inspection, medical and environmental chemical sensing, and so on. Traditional mid-IR detection technologies operating at room temperature are all associated with thermal phenomena that transfer the optical signals into electrical signals through changes of temperature on the device. Here we propose and implement a new signal transducing scheme where the energy transfer path is optical-thermal-mechanical-electrical. By combining highly sensitive strain sensors made with percolative graphene nano-flake films (synthesized by the Marangoni self-assembly method), and highly efficient polymer opto-thermo-actuators, we were able to demonstrate the proof-of-concept bolometric type mid-IR detectors that could be more sensitive than the state-of-the-art technologies. Two types of photoresponse behaviors were observed in our devices: a gradual change in resistance in terms of temperature, which may be associated with the average overlap area decrease of adjacent nano-flakes; and an abrupt "switch" like response that is due to the decrease of the number of conduction paths of the percolative film. Microscopic characterization and theoretical modeling were carried on to understand such behaviors. Theoretical analysis showed that our new technology could be at least one order of magnitude more sensitive than the fundamental limit of existing uncooled mid-IR technologies.

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Research Interests:
Optoelectronics, 2D materials.

Multi-Frequency DEP Characterization of Single Cells

6.12

A. Jaffe, J. Voldman

Sponsorship: National Institutes of Health

We utilize dielectrophoresis (DEP) for label-free cell characterization by cellular electrical properties. We explore the use of DEP to discern the electrical properties of single cells by observing them at multiple input frequencies. We first simulate experimental conditions to show that, by increasing the number of measured frequencies, we are able to better discriminate among different cells using the Clausius-Mossotti factor, a frequency-dependent quantification of how polarizable a cell is. Furthermore, we use the simulation to find the optimal number and values of frequencies to use to best discriminate among different cells in general. We then fabricate a microfluidic device to exploit a force balance between the DEP force induced by a non-uniform electric field and the fluidic drag force on single cells in order to achieve frequency-dependent balance points. We calibrate the device with polystyrene beads and characterize it with BA/F3 cells. We test three different activation levels of HL60 cells treated with Cytochalasin D using the optimal frequency sequence obtained in simulation to determine the differences in discrimination abilities depending on the number of frequencies used. We quantify the discrimination abilities of the optimal one, two, and three frequencies by minimizing 0-1 loss to linearly classify each single cell given its balance point at each frequency.

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Research Interests:
Dielectrophoresis, microfluidic devices, cardiology, ultrasound

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PhD advised by Rajeev Ram.
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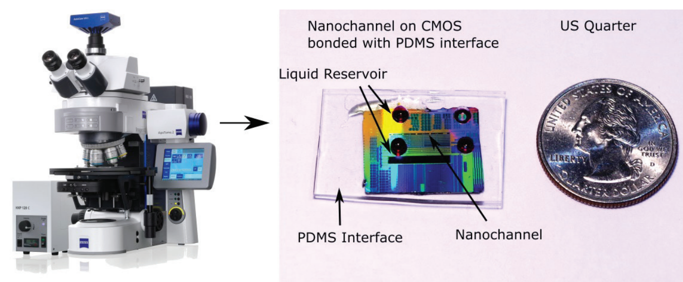
Research Interests:
Biological devices & systems, microfluidic devices & systems, optoelectronics, photonics, silicon.

Integrated Nanofluidics and Photonics on Commercial CMOS

6.13

H. Meng, J. Kim, A. Atabaki, R. J. Ram
Sponsorship: Bose Research Grant

Nanofluidic devices are widely used for fluorescence bioassay. However, most of them require desktop microscopes for readout. Monolithic integration of photonics and nanofluidics enables an on-chip readout. By bringing optical detectors to the near field of the nanofluidic channel, a better collection efficiency and resolution compared to far-field imaging systems are possible. The scalability and precision of the CMOS process enables applications that require high throughput, such as gene mapping and sequencing. We propose an opto-nanofluidic architecture and integrated near-field detection system, leveraging the existing optical devices. By placing silicon based avalanche photodiodes (APD) within the near-field of the nanofluidic channel, the light source emits preferentially into the high index silicon. As a result, a better collection efficiency and resolution of visible wavelengths can be obtained. A method of fabricating nanofluidic channels using polysilicon sacrificial layer is presented. Additionally, a polymer interface connects the nanoscale fluidic channel to a macroscale reservoir. Wetting with water-based solution and electro-osmosis is demonstrated.



◀ Monolithic integration of photodetectors and nanochannels enables an on-chip optical readout.

Direct Observation of Hysteric Behavior of Magnetic Nanoparticles Explaining their Heat Dissipation Behavior

6.14

J. Moon, P. O. Anikeeva
Sponsorship: DARPA ElectRx, Samsung Scholarship

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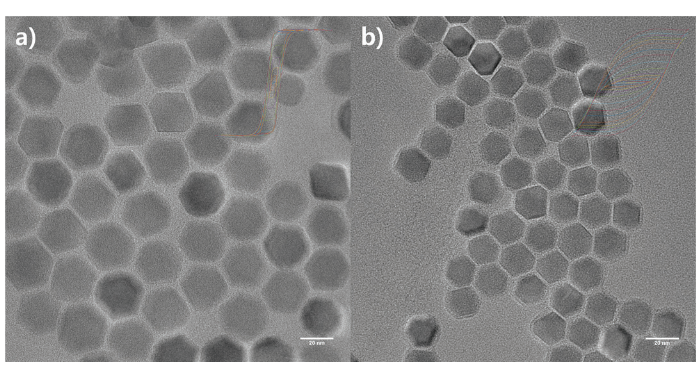
PhD advised by Polina Anikeeva.

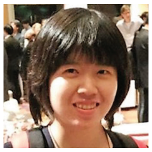
Research Interests:
Magnetic materials, Bio-materials.

Iron oxide magnetic nanoparticles (MNPs) have been widely employed for biomedical application such as MRI agents, cancer treatment, drug releasing and so on. Most of these biomedical applications are strongly dependent on their heat dissipation in the presence of alternating magnetic fields (AMFs) through hysteretic power loss. In many cases, previous work has shown their heat dissipating properties without presenting appropriate models or rigorous studies over various AMF conditions.

In this work we synthesized a broad range of finely tuned MNP sets with linear dimensions ranging 15-30nm and magnetocrystalline anisotropy varied through doping of CoxFe3-xO4 with cobalt at concentrations of x=0~0.25. Dynamic magnetization process of these MNPs has been rigorously measured and compared with their heat dissipating efficiencies under the precisely controlled various AFM conditions.



◀ Figure1 Magnetic nanoparticles and their schematic hysteresis loops. a) Fe3O4 b) Co doped Fe3O4.



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Research Interests:
Nanodevice fabrication, CVD, 2D materials.

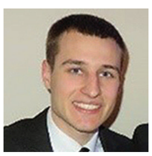
Unleashing Wrinkles in Large-Area Graphene for Electronic Applications

7.01

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

The successful isolation of a single-layer two-dimensional (2D) material (i.e. graphene) in 2004 has led to remarkable scientific discoveries and attracted tremendous research interests arising from its exceptional properties. To date, chemical vapor deposition (CVD) is the most widely used technique to obtain large-area monolayer graphene. Nevertheless, native wrinkles are formed in graphene during the CVD synthesis process, owing to the thermal expansion coefficient mismatch between graphene and the metal growth substrate. The presence of wrinkles in graphene significantly hampers its advantages for electronic applications. Here, we report an elegant technique to unleash the native wrinkles in CVD graphene.

Specifically, we transfer the CVD graphene from its metal growth substrate to arbitrary substrate using a temperature-sensitive polymer-assisted transfer technique. By floating the polymer-supported graphene on hot water (70 - 80 °C), we found that the native wrinkles in graphene can be flattened as a result of tensile force stretching. Through atomic force microscopy studies, we confirmed that our new transfer technique can effectively reduce the number of graphene wrinkles by up to two orders of magnitude. For this study, more than 200 graphene field-effect transistors have been fabricated and tested. We observe that the average field-effect mobility of devices fabricated on graphene transferred using our new technique is 2-3-fold higher than that of conventional PMMA-assisted transfer technique, at the same carrier concentration. We anticipate that the transfer technique presented in this work is applicable for other 2D materials and useful for integration of 2D materials in next-generation electronics. .



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Available from June 2019.

Research Interests:
Optoelectronics, 2D Materials, Nanomaterials

Transition Metal Dichalcogenides with Spatially Controlled Composition

7.02

K. Bogaert, S. Liu, N. Guo, T. Liu, J. Chesin, D. Titow, M. Duchamp, C. Zhang, S. Gradecak, S. Garaj
Sponsorship: SMART-LEES IRG

Two-dimensional transition metal dichalcogenides (TMDs) possess a variety of properties that make them attractive for applications in electronic, energy, and sensing applications. In analogy to conventional semiconductors, more complex heterostructures or alloys based on 2D TMDs would expand the realm of possible device architectures. Therefore, controlled synthesis of complex TMD structures with nanometer or atomic precision is required to unlock their full potential. Here, we present a two-step chemical vapor deposition (CVD) synthesis method to control the spatial composition of the MoS2-WS2 material system and produce structures ranging from an abrupt heterostructure between pure species to a composition-graded or spatially uniform alloy. For the synthesis of each demonstrated structure, the starting material is a CVD-grown WS2 single crystal on its native SiO2 substrate followed by the growth of MoS2.

We show that in-plane diffusion of Mo atoms can play a significant role in the synthesis of MoS2/WS2 lateral heterostructures leading to a variety of non-trivial structures whose composition does not necessarily follow the growth order. The diffusion can be controlled by the point defect concentration in the starting WS2 crystals and/or by the growth temperature of MoS2. Computational analysis indicates that Mo atoms, after adsorbing to edge sites of the WS2 lattice, can diffuse toward the interior of the crystal to displace W atoms and this process is mediated by S vacancies. This pathway is energetically favorable with an activation energy barrier that can be readily overcome at CVD growth temperatures. Optical, structural, and compositional studies of TMD crystals captured at different growth temperatures and in different diffusion stages suggest that compositional mixing vs. segregation are favored at high and low growth temperatures, respectively. In-situ transmission electron microscopy investigation of these temperature-driven processes as well as composition-dependent quantum yield properties of the resulting compositionally-tuned TMD structures will be discussed.

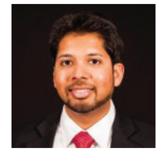
Designing Lubricant-Impregnated Surfaces to Inhibit Corrosion 7.03

S. Khan, K. K. Varanasi

Sponsorship: Statoil ASA

Corrosion is a widespread problem in several industries, and developing surfaces that resist corrosion has been an area of great interest since the last several decades. Super-hydrophobic surfaces that combine hydrophobic coatings along with surface texture have been shown to improve corrosion resistance by creating voids filled with air that minimize the contact area between the corrosive liquid and the solid surface. However, these air voids can incorporate corrosive liquids over time, and any mechanical faults such as cracks can compromise the coating and provide pathways for corrosion. As such, there is a need for self-healing corrosion-resistance surfaces.

In this work, we systematically study the anti-corrosion properties of textured surfaces impregnated with a lubricant. Since corrosion resistance depends on the area and physico-chemical properties of the material exposed to the corrosive medium, we optimize the design of lubricant-impregnated surfaces (LIS) based on the surface tension, viscosity and chemistry of the lubricant and its spreading coefficient on the solid. We perform all corrosion experiments in a standard three-electrode cell using iron, which readily corrodes in a 3.5% sodium chloride solution. In order to obtain textured iron surfaces, we sputter-coat thin films (~500 nm) of iron on silicon wafers textured using photolithography, and impregnate them with lubricants. We show that the corrosion rate on LIS is greatly reduced, and offers an over hundred-fold improvement in corrosion protection. Furthermore, we show that the spreading characteristics of the lubricant is significant in ensuring corrosion protection: a spreading lubricant that covers both inside the texture as well as the top of the texture provides a two-fold improvement in corrosion protection, as compared to a non-spreading lubricant that does not cover texture tops. We also show that an increase in viscosity of the lubricant scales with greater corrosion protection.



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Available from January 2019.

Research Interests:
Surface science, thin films, catalytic materials for CO2 conversion, corrosion protection.

Design of Nanostructured Solid Ionic Hydrogen Barrier Coatings: Engineering Defect Chemistry and Space-Charges 7.04

W. J. Bowman, B. Yildiz

Sponsorship: MITEI

Recent research from Iceland's Krafla geothermal area indicates that hydrogen embrittlement of metallic components is the leading cause of corrosion failure in geothermal systems, whose components operate in extreme environments. Hydrogen is a byproduct of corrosion in water-containing environments, such as geothermal fluid—a high-temperature heat transfer medium. And while protons should ideally be discharged from the solid-liquid interface into the liquid phase as gaseous H2, some atomic and/or ionic H is absorbed by the solid as point defects, ultimately inducing embrittlement and making the metal increasingly susceptible to fracture. For H uptake to occur, it must penetrate a synthetic or native surface layer (e.g. oxide, sulfide, carbonate), which involves interfacial and bulk solid-state ionic processes, including surface adsorption and absorption, as well as bulk diffusion. Hence, there is a significant opportunity to elucidate these processes, and to engineer solid ionic barrier coatings that mitigate H uptake and embrittlement in geothermal systems and metal components employed elsewhere.

Here we aim to develop a solid ionic H barrier coating by employing design and engineering approaches to (i) minimize the H point defect solubility and mobility in the coating material, and (ii) enhance electron transfer from the coating surface to adsorbed protons to accelerate the evolution of H2. We employ a doping strategy for monoclinic ZrO2 based on a recently-developed theoretical framework that predicts the predominant H point defects and their solubility in this oxide. Based on this framework, promising dopant candidates are considered for exploring phenomena (i) and (ii) above. Thermal desorption spectroscopy is employed to characterize low-concentration H solubility in these oxides. Alternatively, we attempt space-charge engineering using solid-solid heterointerfaces to enhance surface activity towards the proton reduction and H2 evolution reactions to reduce proton uptake. Processes are investigated on model thin film samples electrochemically and/or spectroscopically.

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Research Interests:
Materials, oxides, electrical properties, nanoscience, transmission electron microscopy.

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Research Interests:
Micro-texture, Adhesion / Adsorption.

Shielding Surfaces with Texture

7.05

H. L. Girard, D. Soto, K. Varanasi

Drops impacting on solids are ubiquitous: for example rain, sprays and aerosols. It is often beneficial to control various transport phenomena occurring during the impact, such as heat transfer, chemical reactions, or salt deposition. Here, we report a mechanism allowing an order of magnitude reduction in the interaction of an impacting droplet with a substrate, as defined by the integral of the wetted area over time. The reduction is achieved through a macrotexture imprinted on the hydrophobic solid. We establish design guidelines to optimize the texture parameters as a function of drop diameter and Weber number. Finally, we show how this texture can be replicated and can shield a surface from transferring heat to impinging droplets.

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Postdoctoral associate advised by Bilge Yildiz.

Research Interests:
Computational modeling of materials activity and stability.

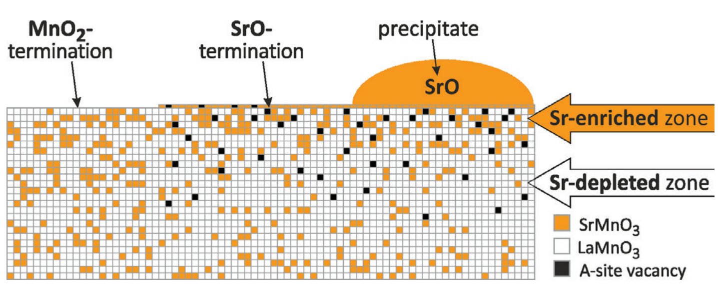
Atomic-Scale Transformation of Terminations at LSM25 Surfaces Modeled by DFT

7.06

F. Hess, B. Yildiz

Sponsorship: Deutsche Forschungsgemeinschaft (DFG)

Doped perovskite oxides are widely applied in electronic devices, where surfaces and interfaces govern material properties. Aliovalently doped perovskites, such as La(1-x)SrxMnO3 (LSM), can form segregation layers capping the surface during operating conditions that are detrimental for material properties, thus degrading the material over time. Reduction of strain energy due to cation size mismatch and electrostatic interaction with a space charge zone in the near-surface region have been proposed as the key aspects leading to cation segregation. We study the experimentally observed initial replacement of statistically mixed MnO2, LaO and SrO terminations by a pseudomorphous monolayer of SrO in LSM25 by computational methods. The resulting SrO surface is less polar than the MnO2 (-1) and LaO (+1) terminations, weakening the proposed space-charge zone. We further propose a mechanism for further Sr segregation, resulting in the formation of SrO particles on the surface.



◄ Starting from pristine LSM25 with dominating MnO2 termination (left) Sr segregates to the surface, forming a capping layer of SrO (center). SrO particles form by further segregation of Sr (right).

Direct-Write Assembly of Functional Colloidal Materials

7.07

A. T. L. Tan, J. Beroz, M. Kolle, K. Kamrin, A. J. Hart

Sponsorship: National Science Foundation

Self-assembly of colloidal particles offers unprecedented opportunity to design and build materials that exhibit emergent properties arising from their atomic composition, the nanoscale ordering of individual particles, and the material's bulk form. However, to date, self-assembly of colloidal materials is limited to the fabrication of films and planar patterns. Here, we present a direct-write technique that enables colloidal crystals to be fabricated with complex, freestanding geometries and centimeter-scale dimensions. We demonstrate the assembly of photonic bandgap materials from polymer particles, and show that the technique can be generalized to a diverse range of particles, including plasmonic metal nanoparticles and semiconducting quantum dots.

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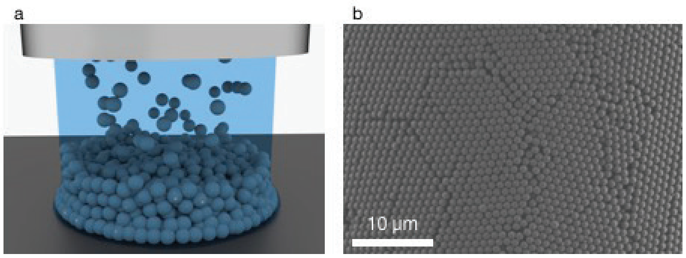
Research Interests:
Colloidal assembly, additive manufacturing.



◄ (a) Direct-write assembly is performed by dispensing a solution of colloidal particles from a fine needle. (b) The surface of the resulting colloidal structure imaged by scanning electron microscopy.

3-D Printed Multi-Material Miniature Diaphragm Vacuum Pumps with Improved Performance and Lifetime

7.08

A. P. Taylor, L. F. Velásquez–García

Sponsorship: Edwards Vacuum

Miniaturized analytical instruments require miniaturized vacuum pumps to extend their autonomy and deployability. We report the first demonstration of a multi-material, fully additively manufactured, miniature diaphragm pump for creation and maintenance of low vacuum from atmospheric conditions. Polyjet 3-D printing technology is used to make a single-stage vacuum pump with active valves and a 1 cm^3 pumping volume. The components of these devices are made of flexible material with different stiffness, greatly extending performance and lifetime compared to our initial results using a single material. While being actuated pneumatically at 1.82 Hz, the devices consistently pumped down a 1 cm^3 volume from atmospheric pressure to 110 Torr in under 4 seconds, and the pumps can deliver mass flow rates as high as 200 sccm at 535 Torr. Compression chamber diaphragms exhibited lifetimes approaching 1 million cycles, while the valves membranes have not leaked after over 2 million cycles.

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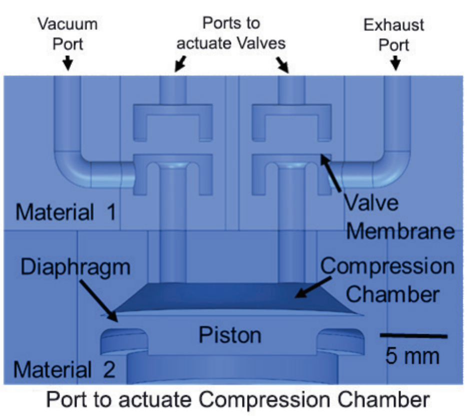
Application Technologist, Edwards Vacuum, visiting Research Scientist, MIT.

Research Interests:
Additive manufacturing of miniature vacuum pumps and actuators, vacuum MEMS, 2D materials for sensors.



◄ A CAD drawing of the two-material diaphragm vacuum pump. The cross-section is through the center of the valve block (upper) made of material 1 and compression chamber block (lower) made of material 2.

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PhD advised by Nicholas Fang.
Available from August 2018.

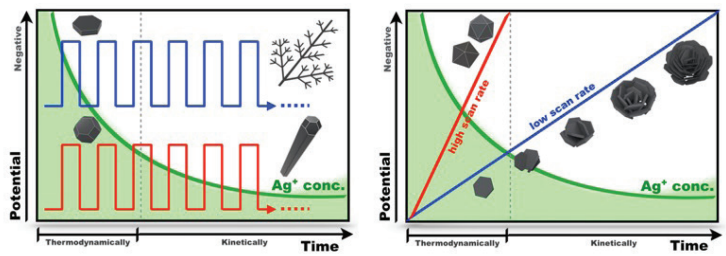
Research Interests:
Electrochemistry, nanomaterials, nanotechnologies, photonics, sensors, energy harvesting devices.

A Universal Electrochemical Approach to Convert Thin Metal Film into Functional Metal Nanocrystals

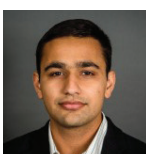
7.09

C. Liu, N. X. Fang, S. P. Feng

Metal and semiconductor nanocrystals (NCs) have attracted great attention due to their fascinating size- and shape-dependent properties for various applications, such as catalysis, sensing, drug delivery, and bio-imaging. Particularly, the synthesis of functional nanocrystals with high surface-to-volume ratios and high-index planes is of significance to achieve enhanced catalytic activities or optical properties. A new electrochemical approach, named as cyclic scanning electrodepostion (CSE) method, is proposed to convert a thin metal film into varied metal or metal oxide NCs with a wide range of surface-to-volume ratios, in shapes such as nanoflowers, nanorods, dendrites, polyhedrons, and concave octahedrons. The core of this process is a specific electrolyte consisting of CH_3COONa, $NiSO_4$, and Na_2SO_4, and this technique deals with potential waveforms, population of adions, and foreign ions in a methodical manner. The flower-like Ag NCs have demonstrated remarkably enhanced catalytic activity for electro-oxidation of glucose.



◄ Schematic diagram for the shape-controlled mechanism of Ag NCs via cyclic scanning electrodeposition.



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PhD advised by Eugene Fitzgerald.
Available from September 2018.

Research Interests:
Epitaxy, Heterointegration, Materials defects, Photovoltaics.

Removal of Threading Dislocations in (In)GaAs/Si on by their Glide to Mesa Sidewalls

7.10

R. Shah, E. A. Fitzgerald

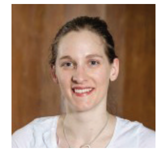
Sponsorship: US Department of Energy ARPA-E, SMART

Growth of semiconductors like Ge and III-V alloys on Silicon can add functionality to electronic devices while leveraging the low cost, high throughput infrastructure of Silicon based manufacturing. Since the lattice constant of these semiconductors are different than that of Silicon, the strain is relieved by plastic deformation. While misfit dislocations are desired for this plastic relaxation, their threading segments intersect the device's active area degrading device performance. To mitigate these defects, two approaches have been well explored in literature – minimizing defect nucleation and encouraging defect annihilation reactions, both having their limitations.

We studied a less explored scheme, of introducing dislocation sinks by patterning substrates to create free surfaces and engineering the strain in the epitaxial films to drive the dislocations to glide towards mesa edges. By changing the amount of Indium in $In_xGa_{1-x}As$ we demonstrate a 50% reduction in defect density of InGaAs/Ge/Si. The resultant defect density of $5x10^6$ cm^{-2} is low enough to make efficient photovoltaic cells that are comparable to those made on GaAs substrates. For high Indium content, we observe additional nucleation of dislocations, setting an upper bound to the amount of strain that can be utilized for the desired glide of mobile dislocations.

Control of SrTiO3 Resistive Switching by Adhesion Layer Doping

7.11



E. Sediva, W. Bowman, J. L. M. Rupp
Sponsorship: SNF, Swiss National Science Foundation

Current computer memory limitations call for high-speed, low-power, non-volatile devices that would close the latency gaps in the computer memory hierarchy. Oxide based resistive switches are one of the emerging candidates. Several performance issues such as variability or endurance are key to bring this technology to the market. In this study we address the control over the switching process by altering a metallic adhesion layer bellow the bottom electrode. Yang et al. have previously shown that the adhesion layer can seed switching sites in a TiO_{2-x}-based device by diffusing through the bottom electrode material at higher temperatures.

We focus in this study on a different switching material, namely strontium titanate ($SrTiO_3$), which has often served as a model material to investigate emerging non-volatile memories. Using transmission electron microscopy (TEM) we prove that diffusion of the adhesion layer through the bottom electrode is taking place. Additionally, in the case of a Cr-adhesion layer, we prove using Raman spectroscopy that doping of the switching oxide ($SrTiO_3$) by the Cr adhesion occurs. Doping on the B-site of the $SrTiO_3$ perovskite at the bottom interface turns out to have large consequences on the switching behavior. From current-voltage profiles we prove that the switching process is completely suppressed when a Cr adhesion layer is used. Using the sensitivity of Raman to local atomic rearrangements we use in-situ oxidation and reduction experiments to link the spectra to the materials switching property. In conclusion, we use a metallic adhesion layer to selectively dope $SrTiO_3$ serving as a switching material to understand the switching process and the defect chemistry of the system. Our findings support the fact that each memory device system follows very different switching mechanisms creating a plethora of possible nano-devices.

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Research Interests:
Materials science, solid state ioinics, defect chemistry, resistive switching.

Stabilization of Metal Halide Perovskite Nanoplatelets for Fundamental Studies and Optoelectronic Applications

7.12

S. K. Ha, W. Paritmongkol, W. A. Tisdale
Sponsorship: The Center for Excitonics

Metal halide perovskites have recently emerged as one of the most promising semiconductor materials for optoelectronic applications owing to their bright luminescence, long charge carrier diffusion length, defect tolerance, facile compositional tunability, and ease of synthesis. Two dimensional nanoplatelets made from metal halide perovskites have well-defined thicknesses and are only a few unit cells thick. These nanoplatelets exhibit further distinctive features such as large exciton binding energies, dimensional tunability, and spectrally narrow emission/absorption spectra. However, fundamental studies and practical application of perovskite nanoplatelets are limited by the poor stability of the material. Our primary goal is to address this stability issue.

Perovskite nanoplatelets have the chemical formula of $L_2[ABX_3]_{n-1}BX_4$ (L: Organic ligand cation, A: monovalent metal or organic molecular cation, X: halide anion) where n-1 indicates the platelet thickness in unit cells. In this work, colloidal perovskite nanoplatelets were synthesized at room temperature by a facile anti-solvent crystallization method with varying thickness (n=1 or n=2) and composition. We achieved platelets with relatively large lateral dimensions that exceed 1μm. Subsequently, several practical techniques that enhance the stability of these perovskite nanoplatelets in colloidal solution and in thin film morphologies were demonstrated. The stabilization of perovskite nanoplatelets enables further probing of their photophysical properties and future optoelectronic applications. Notably, perovskite nanoplatelets are one of the leading candidates for efficient deep-blue light emitting devices due to their spectrally narrow deep-blue emission which primarily occurs in the direction normal to the nanoplatelet surface. Such directional emission has the potential to improve light emitting device efficiency by improving outcoupling from the device stack. However, it has been reported that LEDs utilizing two-dimensional perovskite emitters suffer degradation under applied bias. Stabilized perovskite nanoplatelets are expected to alleviate this problem and further improve device stability.

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Research Interests:
Nanomaterials, nanotechnology, 2D materials, exciton dynamics, optoelectronics

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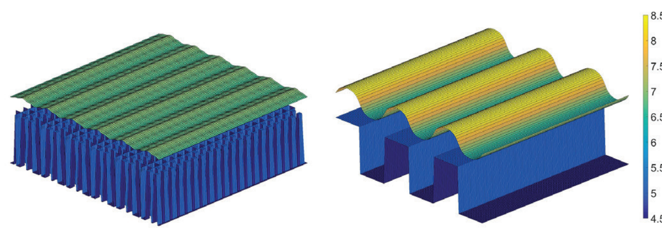
Research Interests:
Process modelling, machine learning, optimization, and process control.

Modelling and Controlling Variations in 2.5D Packaging

7.13

C. Lang, D. Boning
Sponsorship: TSMC

Re-distribution layers (RDLs) are wafer level wiring layers dedicated to connecting separately fabricated die to one another and to external I/O ports. Previously, these RDLs were most commonly fabricated using the Damascene process; however, foundries have recently adopted processes that utilize more cost efficient semi-additive plating instead. Due to the lack of chemical mechanical planarization (CMP) in these cost-efficient processes, non-uniformities in both the electroplating and the spin coating step can lead to serious lithography and electrical performance issues. Our recent work has focused on predicting and modelling these variations based on the interconnect layout, as well as developing fill algorithms that ensure planarity after each process. As variations in both processes are caused mainly by differences in pattern densities within the layout, these algorithms augment existing layouts to keep densities approximately constant throughout the design.



◀ Simulation results showing underlying structure and coated surface (in µm) after spin coating without (left) and with (right) fill patterns. Here, the dimensions of the structures shown are both 60 µm x 60 µm.

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Research Interests:
Machine learning, modeling advanced IC technology.

Online and Incremental Machine Learning Approaches for IC Yield Improvement

7.14

H. Chen, D. Boning

In the competitive semiconductor manufacturing industry where large amounts of data are generated, data driven quality control technologies are gaining increasing importance. In this work, we build machine learning models for high yield and time varying semiconductor manufacturing processes. Challenges include class imbalance and concept drift. Class imbalance (relatively small number of failure training examples) is due to high manufacturing yield. Concept drift refers to unexpected or unknown changes in the statistical properties of the dataset. Batch and online ensemble machine learning techniques are proposed to address the problem of class imbalance. An incremental learning framework which combines the classifiers trained on different data chunks is designed to overcome the problem of concept drift. We study the packaging and testing process in chip stack flash memory as an application.

We build a mathematical model and demonstrate the possibility of yield improvement using a classifier to detect bad dies before packaging. Experimental results demonstrate significant yield improvement potential using real data from industry. Without concept drift, for stacks of 8 dies, an approximately 9% yield improvement can be achieved. In a longer period of time with realistic concept drift, our incremental learning approach achieves approximately 1.4% yield improvement in the 8 die stack case and 3.5% in the 16 die stack case, which are 4.4× and 1.5× of the yield improvement by a single classifier trained only on the most recent data.

New Photolithography Capabilities at MTL

7.15

K. Payer, D. Ward, D. Terry
Sponsorship: MTL

MTL has recently added new photolithography tools to enhance the Lab's capabilities, improve user throughput, and promote process design flexibility. The Karl Suss MA6 mask aligner was relocated from TRL to EML, and brings 6 inch exposure capability and improved alignment to an expanded user base. Replacing the MA6 in TRL is an OAI Flood Exposure unit that has a simplified user interface for the image reversal photolithography process as well as first-level mask exposures (including transparency masks) on standard and SU8 lithography processes.

The Heidelberg MLA-150 Direct-Write Maskless Aligner has been added in TRL. This tool allows for direct writing of patterns using one of two lasers (375 nm and 405 nm) along with contactless alignment with precision down to 500 nm. The tool can write features with 1 um resolution, which bridges a gap between traditional contact lithography and stepper lithography. A major benefit to this tool is the flexibility to allow users to modify designs quickly from substrate to substrate without the need of a new mask. The MLA-150 also has relatively fast throughput: from 30-45 minutes for a full wafer exposure down to 1 minute exposures for small pieces.

In ICL a PicoTrack PCT-200CRS has replaced the SVG coater track with added capabilities. The new, robot-driven track brings 6 inch and 8 inch coating, baking and developing processes for both CMOS compatible wafers (MTL "green" wafers) and Au-III-V contaminated wafers (MTL "red" wafers). The PicoTrack has facilities for two standard photoresists in large format bottles as well as a syringe-pump dispense for alternative photoresists; the develop track has capabilities for two different developers. This tool brings improved throughput and uniformity to wafer-scale photolithography processes of all varieties.

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MTL Staff; Process Development & Equipment.

Online Tools for Process Design, Compatibility Check, and Cost Estimation

7.16

J. Scholvin

This poster presents a functional overview of the user-created MTL Fab website, and its underlying architecture. The new Fab website has two main goals: First, to make it easy for new and prospective users to learn about equipment, identify suitable tools, and build a process. Second, to provide experienced users with a library of recipes and documents, and ideas for alternative equipment. Tool descriptions were created by experienced students and postdoc users over the last years, and highlight equipment from the user's perspective. The focus is on short descriptions that include specific notes on what a particular tool is best suited for, and what its limitations are. Data sheets, SOPs, images, links, and recipes can be attached to provide further insights. A key function is the ability for users to select tools and build a process flow online.

The resulting process is automatically verified against tool and material choices in real time to flag potential problems, and can be exported into a spreadsheet and PDF format for process approval submission. In addition, common process modules (such as lithography, SU8 molds, or metal deposition by liftoff) are available as one-click presets, allowing users to quickly build a simple process with good tool choices and baseline recipe parameter suggestions. Finally, a cost estimation capability is implemented to help users estimate tool time and costs. The website itself is generated off-line from a set of tables that capture the tools and their descriptions, and this data is then used by scripts to auto-generate the set of individual html pages, including cross-links and indexes of the contents. This approach, while unorthodox, generates a simple set of static html pages without any need for server side code or databases, making it very fast and simple to deploy the site.

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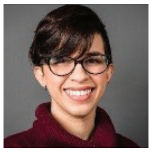
Research Interests:
Microfabricated neural recording devices. Electrophysiology, Bio-MEMS, packaging, design



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Development of an Embedded Platform for Tracking of Alzheimer's Disease

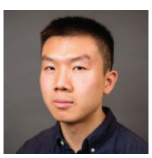
8.01

G. S. Peña, H. Lai, T. Heldt, V. Sze

Sponsorship: General Electric Company

Alzheimer's Disease (AD) is the sixth-leading cause of death in the US, with the total estimated annual costs associated with it around $259 billion. Currently, there are no treatment options to prevent, cure, or slow down its progression. AD diagnosis requires patients to undergo time consuming neuropsychological tests that suffer from high-retest variability, making it difficult to assess the progression of the disease or a patient's response to experimental treatments. We propose to tackle the lack of an objective measurement to track the progression of AD by designing tools that can quantify subtle changes across time in a set of digital biomarkers that correlate with disease progression. Digital biomarkers generated with consumer electronic devices are readily accessible and can be collected repeatedly and unobtrusively. Specifically, we will assess and track features of eye movements that have been shown to be affected by AD progression.

One such feature is saccade latency – the time delay between the appearance of a visual stimulus and when the eye starts to move towards said stimulus. Repeat measurements of saccade latency can be taken unobtrusively over time to help reduce measurement variability, providing an objective, quantifiable metric with higher granularity than current diagnostic tests. As a result, a tool that measures saccade latency (or other metrics of eye movement) consistently across time can enable the quantification of disease progression and the assessment of a patient's response to treatment. Our aim is to bridge the gap between state-of-the-art computer vision algorithms and traditional clinical eye-movement measurements by designing, testing, and validating a suite of algorithms optimized for embedded systems that can measure eye movement patterns to clinical precision. These techniques will be evaluated against multiple parameters, but the ultimate evaluation metric will be the variability introduced by our algorithms on the saccade latency measurements.



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Research Interests:
Low-power digital and analog circuit design

Breath Monitoring Using a Low-Power Time-of-Flight Camera

8.02

Z. Ji, A. P. Chandrakasan

Sponsorship: Texas Instruments

Breathing is a physiological signal that can be useful in medical diagnosis, health tracking, as well as sleep and baby monitoring. Current methods for measuring breathing rate involve the patient breathing into an apparatus or placing sensors on their body. Besides being potentially obstructive, these methods could alter the breathing of the patient, resulting in inaccurate measurements. We propose a non-contact system for measuring breathing rate using a low-power low-resolution time-of-flight (ToF) camera (TI OPT8320) that measures depth. One of the main advantages of ToF cameras is their ability of operate in the dark due to the use of infrared illumination, making them suitable for sleep monitoring applications. In addition, the breathing signal can be extracted directly from the depth signal, leading to simpler processing compared to methods that use RGB cameras.

We calculate the breathing rate with a two-part algorithm: (1) the region-of-interest (ROI) is automatically identified using pixel-wise computations; (2) the breathing rate is extracted from the frequency spectrum obtained from the data within the ROI. We created a real-time demo, with the algorithm implemented on an FPGA, where a respiratory belt (containing a pressure sensor) was used to extract the reference breathing rate signal. Our system can track the breathing rate to within 1 breath per minute.

Future directions include implementing dynamic power management techniques to reduce the total system power. For example, if the subject moves closer to the camera, the illumination power can be reduced to a certain point without loss of measurement accuracy. The problem will be to determine the optimal amount to vary the illumination power (and other parameters) based on changes in the scene. These techniques will be important in improving the battery life of the system if it is to be implemented in a portable form factor.

A Non-Invasive Central Arterial Pressure Waveform Estimation System using Ultrasonography for Real-Time Monitoring

8.03

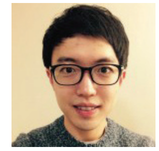
J. Seo, C. G. Sodini, H.-S. Lee

Sponsorship: MEDRC – Philips, CICS

An arterial blood pressure (ABP) waveform provides valuable information in diagnosing and treating cardiovascular diseases of patients. The ABP waveform is usually obtained through a pressure transducer connected to an arterial catheter (A-line). Even though it is considered a gold standard, it has a major disadvantage of being invasive. In addition, hemodynamics studies have been impeded by the lack of reliable non-invasive techniques for monitoring the central ABP waveform. Ultrasonic ABP waveform monitoring is preferable due to its non-invasive nature, which minimizes the potential risks.

The proposed ultrasonic ABP waveform monitoring is achieved by observing the pulsatile change of a cross-sectional area and identifying the elastic property of an arterial vessel, represented by a pulse wave velocity (PWV; the propagation speed of a pressure wave along an arterial tree) and a diastolic blood pressure measurement as a reference point. PWV can be estimated by generating a flow-area plot during a cardiac cycle and measuring the slope of the linear part of the plot during a reflection-free period (e.g., the early systolic stage).

A prototype hardware is designed on a printed circuit board, and the transducer assembly is manufactured using a 3-D printer. The prototype board is capable of driving up to eight channels of electronics and streams data to the PC at above 10Mbps using an USB interface. A clinical test conducted on 9 healthy subjects demonstrates the feasibility of this technique. Currently, the prototype device has been re-designed to overcome several limitations. The new prototype will be used for the clinical study, which will be held at the local hospital in order to compare it with the gold standard A-line measurement.



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Research Interests:
Electronic devices, electronics, integrated circuits, medical devices & systems

Graphene-Based Wireless Sensors in Contact Lenses for Glucose Monitoring

8.04

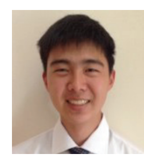
H. Cheung, G. Azzellino, T. Palacios

Sponsorship: MIT UROP

Contact lenses provide a large platform with diagnostic potential in monitoring the many biomarkers found in tear fluid. The easily-accessible body fluid contains continuously-refreshed levels of glucose, cholesterol, and sodium concentrations along with a wealth of other information. Since contact lenses are generally exposed to the environment, they provide unhindered wireless communication to off-board readout sensors.

In particular, continuous metabolite monitoring is extremely attractive in the context of glucose levels for people living with diabetes. Current monitoring methods require pricking a finger and taking a blood sample for an electrochemical glucometer and with recommendations to sample nearly eight times a day. The motivation of this work is to explore the potential of graphene as a passive continuous-monitoring sensor platform, with contact lenses as the medium to connect to the body non-invasively.

We present a passive resonator antenna consisting of a planar spiral inductor and an interdigital capacitor with a layer of functionalized graphene on top of the capacitor. As basal tear fluid is continuously refreshed at a rate of 0.5-2.2 μL/min, targeted metabolites bind to the layers of functionalized graphene and changes the capacitance, and consequently the resonant frequency, of the antenna. An external wireless device interrogates the antenna and measures the reflected signal and analyzes the data to estimated current glucose levels and other data. This sensor demonstrates the feasibility of using graphene as a precise chemical monitoring platform.



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Research Interests:
Medical devices & systems, BioMEMS, MEMS & NEMS, Sensors, Biological devices & systems, Energy harvesting devices & systems.

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Research Interests:
Medical devices, biosensors, neuro-engineering, flexible electronics.

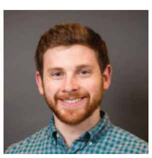
A Stretchable Multielectrode Array for Skeletal Muscle Conditioning and Epimysial Recording During Peripheral Nerve Injury

8.05

M. B. McAvoy, J. K. Tsosie, K. Vyas, O. F. Khan, R. Langer, D. G. Anderson
Sponsorship: Joint Warfighter Medical Research Program, Department of Defense

Highly traumatic skeletal muscle injuries that involve peripheral nerve damage require over a year for repair. While healing, denervated muscles quickly undergo atrophy, which significantly affects functional recovery of motor reinnervation. The common clinical treatment for atrophy uses functional electrical stimulation. However, conventional transcutaneous electrodes are not optimal for cases requiring peripheral nerve repair and can induce significant damage. Intramuscular electrodes are rarely used clinically because of the invasiveness of the approach and the prohibitively large electrode arrays necessary to induce denervated muscle contraction. Conventional epimysial (i.e. on the muscle surface) electrodes are sometimes bulky and unable to meet the stringent needs of peripheral nerve repair.

Meanwhile, little information with regard to the time course of nerve regeneration and motor reinnervation has been collected. There is a need for an effective, continuous interface that is suitable for stimulation of denervated muscle and for the real-time in vivo monitoring of the nerve regeneration time course. Additionally, it is still unclear what the optimal stimulation protocols should be. The objective of this research was to develop an integrated therapeutic/diagnostic approach for improved nerve repair. Here, an implantable microelectrode was developed that provides surface neuromuscular stimulation during long-term denervation. The design consists of embedding an array of gold-based microelectrodes within a thin substrate of biocompatible poly(dimethylsiloxane) elastomer with low water permeability.



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Research Interests:
Medical devices and systems, Nanomaterials, Nanotechnology.

Wireless, Transgene-Free, Animal-Scale Magnetomechanical Neural Stimulation via Magnetic Vortex Magnetite Nanodisks

8.06

A. Senko, D. Gregurec, P. Reddy, S. Rao, M. Christiansen, P. H. Chiang, S. Park, P. Anikeeva
Sponsorship: DARPA, NIH, NDSEG

A new technique has been developed for magnetic nanoparticle-based neural stimulation. Unlike magnetothermal neural stimulation, which is based on the transfection of neurons to sensitize them to heat, this magnetomechanical approach does not rely on transgenes, making it potentially safer for clinical applications. Unlike other magnetomechanical stimulation techniques, in which neurons are typically hundreds of microns or less from a magnetic field source, the field required for this technique is produced at the scale of an entire rat using a simple solenoid and a 200 W audio amplifier. This advantage in stimulated volume is enabled by magnetic particles with volumes hundreds of times larger than conventional magnetic nanoparticles, but which have favorable colloidal properties due to their disk shape. These magnetite nanodisks possess a magnetic vortex state, which nearly eliminates stray field and results in less inter-particle attraction compared to spherical magnetic particles of similar volume. The neural stimulation technique enabled by these magnetic nanodisks has been demonstrated to robustly induce calcium influx in whole dorsal root ganglion culture. Minimally invasive neural stimulation techniques are of interest for treating neural disorders such as Parkinson's disease.

Representation of Complex Auditory Stimuli in the Mammalian Brainstem

8.07

D. Lyzwa

The inferior colliculus, a recent target for an auditory prosthesis, is investigated to improve electric stimulation algorithms. Complex sound representation in this main center of convergence in the midbrain is not yet well understood. The representation of neural spiking responses to artificial and natural sounds across this subcortical nucleus is analyzed based on neurophysiological multi-unit tetrode-recordings from the inferior colliculus of anesthetized guinea pigs. The specific-specific vocalizations display various envelope types and spectral contents. Using cross-correlation, we compare the predicted and recorded temporal neural responses for two approaches: a modification of the biophysically detailed Meddis model, and a filtering approach around the neuron's preferred frequency, using then the rectified response. The filtering approach yields better predictions than the biophysically detailed model for the compound response from groups of neurons for all of the vocalization, onsets are better captured as well as phase-locking (Lyzwa, IJCNN 2015). A frequency-selective representation thus well captures the compound response from a group of neurons to natural sounds. Additionally, a prediction model of temporal spiking responses of single neurons in the inferior colliculus to novel complex sounds, including linear and nonlinear neural response properties is presented.

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Research Interests:
Quantum optics, defect centers in diamond, biosensing, computer neuroscience.

Simulation and Fabrication of Chip to World Interface for CMOS Opto-nanofluidic Chip

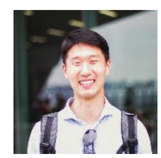
8.08

J. Kim, H. Meng, R. J. Ram

Sponsorship: Bose Foundation and Kwanjeong Educational Foundation

Lab-on-CMOS is an attractive platform for a myriad of bio-sensing applications. This is because it offers the capability to integrate complex fluidics, photonic sensing elements, and electronic signal conditioning circuitry all on a single chip. Such integration could potentially enable more sensitive and higher throughput measurements in biomolecular sensing applications, such as DNA mapping and protein sequencing. Our group has previously demonstrated the fabrication of sub-100 nm nanofluidic channels on a CMOS chip using sacrificial XeF2 etch.

This poster presents work in progress to develop a chip-to-world interface that enables the opto-nanofluidic CMOS platform to demonstrate its full capabilities. The opto-nanofluidic chip requires fluidic connections that deliver the analyte to the active sensing region, a readout in order to sense the signal, and a control method of driving the fluid motion. Fluidic connections were realized by Polydimethylsiloxane (PDMS) micro-channels and were bonded to the opto-nanofluidic chip by conventional plasma bonding using a custom-built alignment stage. In order to support standard die sizes, a wafer reconstruction method was developed to embed the die in a support material that has sufficient area to bond to the PDMS micro-channels. Readout connections were implemented using standard gold electrode deposition and lift-off process. Finally, COMSOL simulation of the fluid movement and electro osmosis will be run to examine the limits of fluid control precision and estimate the achievable throughput with the opto-nanofluidic platform.



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Biological devices & systems, micro nanofluidics, optoelectronics, photonics, Si.

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Photonic sensing, biosensing, MEMS, nanotechnology, wearable technology.

On-Chip Photonic Aerosol Spectrometer for Detection of Toxic Inhalable Materials

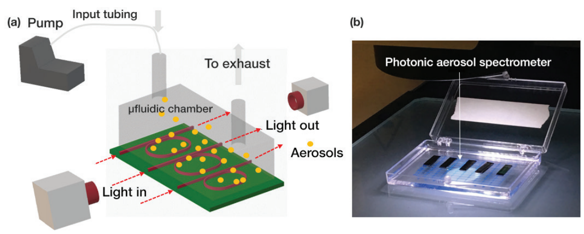
8.09

R. Singh, D. Ma, A. Agarwal, B. Anthony

Aerosol particles are distributed in the atmosphere and can constitute serious health threats depending on their chemistry, size, and concentration. For instance, particles of different sizes are deposited in different parts of a lung airway and can lead to specific respiratory complications; and aerosols with certain functional groups can be more harmful than others. So, the comprehensive sensing of aerosol particles is critical for human health, particularly with timely monitoring of environmental pollution, industrial pollution and defense threats.

Most existing aerosol sensors are based on free-space detection methods using optical scattering, IR spectroscopy, and electrical property determination. These sensors can suffer from poor sensitivity, and be expensive and bulky.

We have developed an on-chip photonic aerosol spectrometer that can perform in-situ particle sizing, counting, shape and chemical characterization. The technology offers various advantages in particle sensing modalities by offering improved sensitivity, response time and reduced cost and size of the device.



◄ Schematic of the setup used in on-chip aerosol spectroscopy. It comprises of three different parts namely (a) Aerosol delivery and transport system (b) On chip photonic sensing system (c) Output pattern and spectrum acquisition system. (b) Fabricated photonic aerosol spectrometer.

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Research Interests:
Microfluidics, acoustofluidics, advanced manufacturing, bioprinting, microsystems engineering.

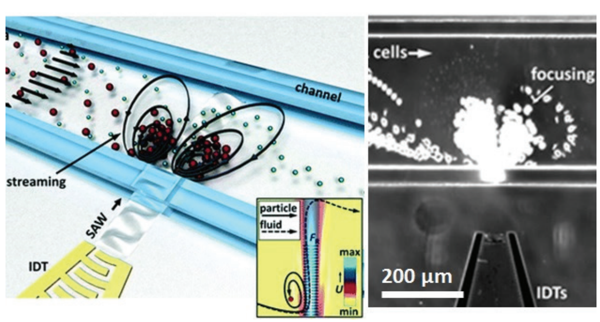
Continuous Cell Sorting with High Frequency Acoustic Waves

8.10

D. J. Collins, B. L. Khoo, Z. Ma, A. Winkler, R. Weser, H. Schmidt, J. Han, Y. Ai

Sponsorship: Singapore MOE, NMRC, NRF, Prime Ministers office (CREATE), SMART, BioSyM

Acoustic streaming is a promising candidate for fluidic micromanipulation, where the nonlinear propagation of acoustic energy through a dispersive media gives rise to a body force in the propagation direction. Whereas most systems utilizing acoustic fields attempt to minimize this effect for patterning and sorting applications, we intentionally maximize it to generate strong rotational vortices that can be used for size-elective cell and particle capture. This is accomplished through the use of a highly focused surface acoustic wave (SAW) beam (~25 μm width), which increases the acoustic force gradients that generate these vortices and particle forces. Particle and cell migration in this field is a result of the combined acousto/fluidic forces in the vicinity of this focused beam. We demonstrate the selective capture of 2 μm from 1 μm polystyrene particle populations and human breast adenocarcinoma cells (MDA-231) from red blood cells in a continuous flow.



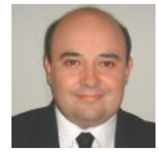
◄ Micro-vortices from acoustic beams can be used for selective capture in microfluidic systems. (Left) Concept image showing size-selective particle capture. Inset shows divergence between particle pathlines and fluid streamlines. (Right) Image stack of MDA-231 cells captured in micro-vortices.

Wound Model in a Skin-on-a-Chip Microdevice

8.11

G. Ascencio-Favela, R. Chandra, J.S. Garcia-Perez, R. Parra-Saldivar
Sponsorship: School of Engineering, ITESM

Organs-on-a-chip are micro-devices with the aim to replace preclinical testing and convey a realistic idea of the human physiology. This technological advance will have a great impact on the pharmaceutical industry because it avoids ethical complaints on animal testing and represents a massive cost reduction of non-viable drugs testing. With this model, only drugs that show promising results on the organ-on-a-chip system would be selected. The dermatological industry looks forward to relying entirely on skin-on-a-chip models. There exist several wound healing and drug-delivery skin models. Those models have either all skin layers (Human Skin Equivalent) or just the top layer (Reconstructed Human Epidermis) and are static models. As a proof of concept to further develop a human cell line model, in this study, a skin-on-a-chip microdevice is fabricated. The model consists on a layer of murine fibroblasts and a layer of porcine stratum corneum on top. Within the chip, the interaction of a pathogenic strain (S. aureus) is studied by adding a suspension of different concentrations of the bacteria. The additional advantages of the system are that the model is dynamic, allowing a flow of nutrients under the fibroblast culture, and has an Air-Liquid Interface. The bacteria are able to trespass the layers is quantified by CFU-counting performed on the exiting medium. The number of bacteria and a healthy fibroblast cell culture is being compared to that of an incision and a burn wound within the model.



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Research Professor at ITESM.

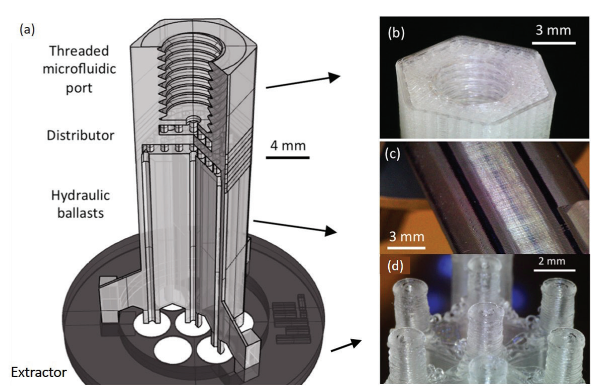
Research Interests:
Microdevices, Organ-on-chip, Cell culture, Drug delivery.

Biocompatible Dielectric-Conductive Microsystems Monolithically 3-D printed Via Polymer Extrusion

8.12

Z. Sun, L. F. Velásquez-García

Monolithic multi-material 3-D printing has the potential to implement better, more complex, and more capable microsystems at a small fraction of the time and cost typically associated with semiconductor cleanroom microfabrication. Here we report additively manufactured microsystems composed of conductive and dielectric layers using a fused filament fabrication (FFF) dual extruder 3-D printer. The base material is polylactic acid (PLA) -a biocompatible polymer that can be doped with micro/nanoparticles to become electrically conductive. Characterization of the printing technology demonstrates close resemblance between CAD files and printed objects, generation of watertight microchannels, high-vacuum compatibility, and non-cytotoxicity. A large (~23) piezoresistive gauge factor was measured for a certain graphite-doped conductive PLA, which suggests its utility to create strain transducers. Basic electrical components, cantilevers, and multiplexed electrohydrodynamic liquid ionizers with integrated extractor electrode and threaded microfluidic port were demonstrated.



◄ CAD schematic and selected close-up views of FFF-printed 7-emitter electrospray array with hydraulics made of dielectric PLA and extractor electrode made of graphite-doped conductive PLA.

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SM advised by Luis Fernando Velásquez-García.
Available from June 2018.

Research Interests:
3-D printing of detail-rich, vacuum-compatible, and miniaturized microsystems.

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Available from May 2018.

Research Interests:
Additive Manufacturing, Microfluidics, Biomedical Engineering

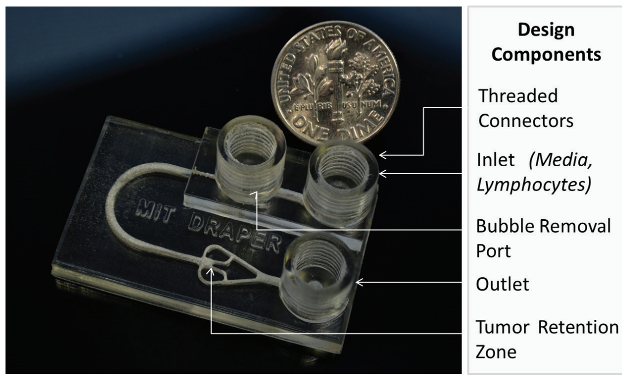
3D Printed Microfluidics for the Evaluation of Immunotherapy Treatments

8.13

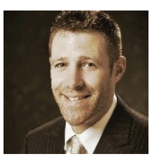
A. L. Beckwith, J. T. Borenstein, L. F. Velásquez-García

Sponsorship: Draper, DoD

Inherent challenges in device fabrication have impeded the widespread adoption of microfluidic technologies in the clinical setting. Additive manufacturing could address the constraints associated with traditional microfabrication, enabling greater microfluidic design complexity, fabrication simplification (e.g., removal of adhesion and bonding process steps), and rapid and inexpensive design iterations. We report the development of an entirely 3D-printed microfluidic platform that enables modeling of interactions between tumors and the immune system, providing a microenvironment for testing the effectiveness of immunotherapy treatments. The developed platform allows for the analysis of interactions between a resected tumor fragment and circulating lymphocytes in the presence of immunotherapy agents. Human tumor fragments were successfully loaded into the printed microfluidic device and imaged via fluorescence microscopy. Our high-resolution, non-cytotoxic, transparent device monolithically integrates a variety of microfluidic components into a single chip, greatly simplifying device operation.



◄ Design features of a 3D-printed, transparent, non-cytotoxic microfluidic platform for analysis of the effectiveness of immunotherapy



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Research Interests:
Surgical technologies and devices.

Laser-Machining Biological Tissues

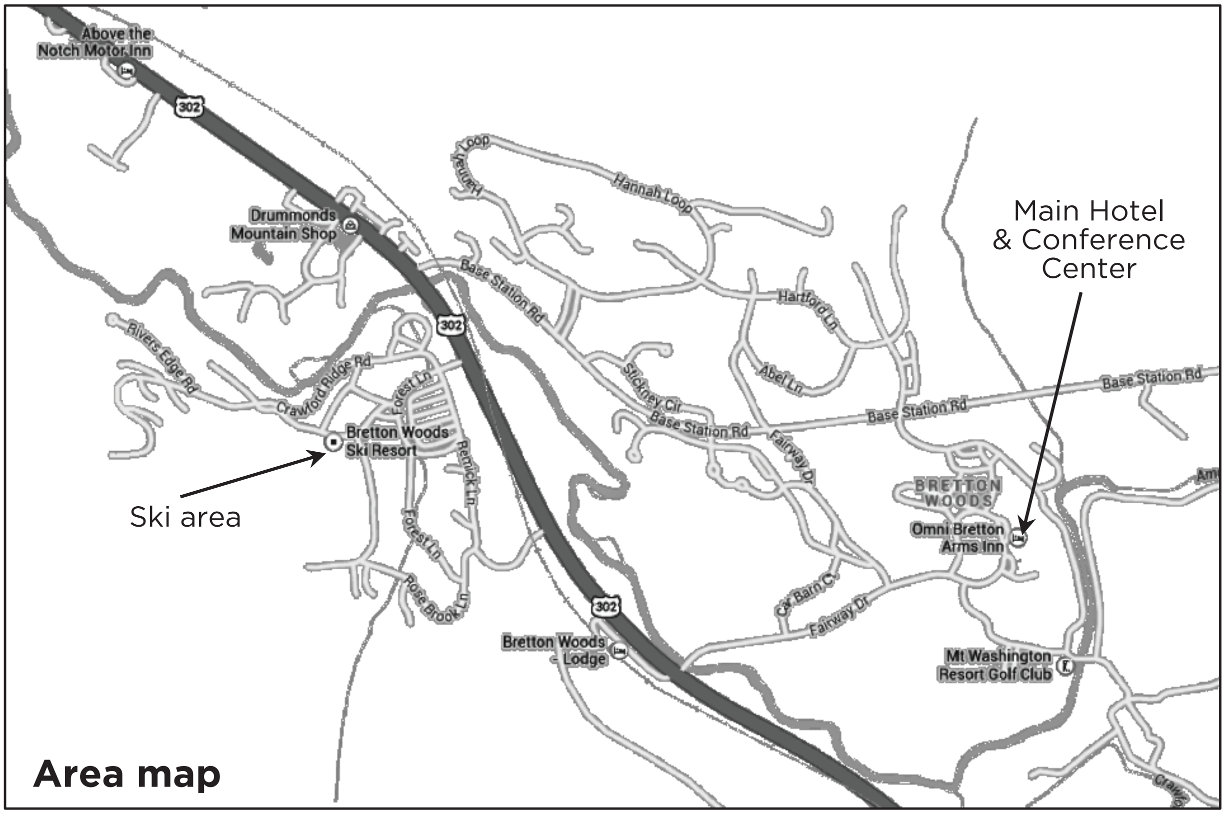
8.14

M. Johnson

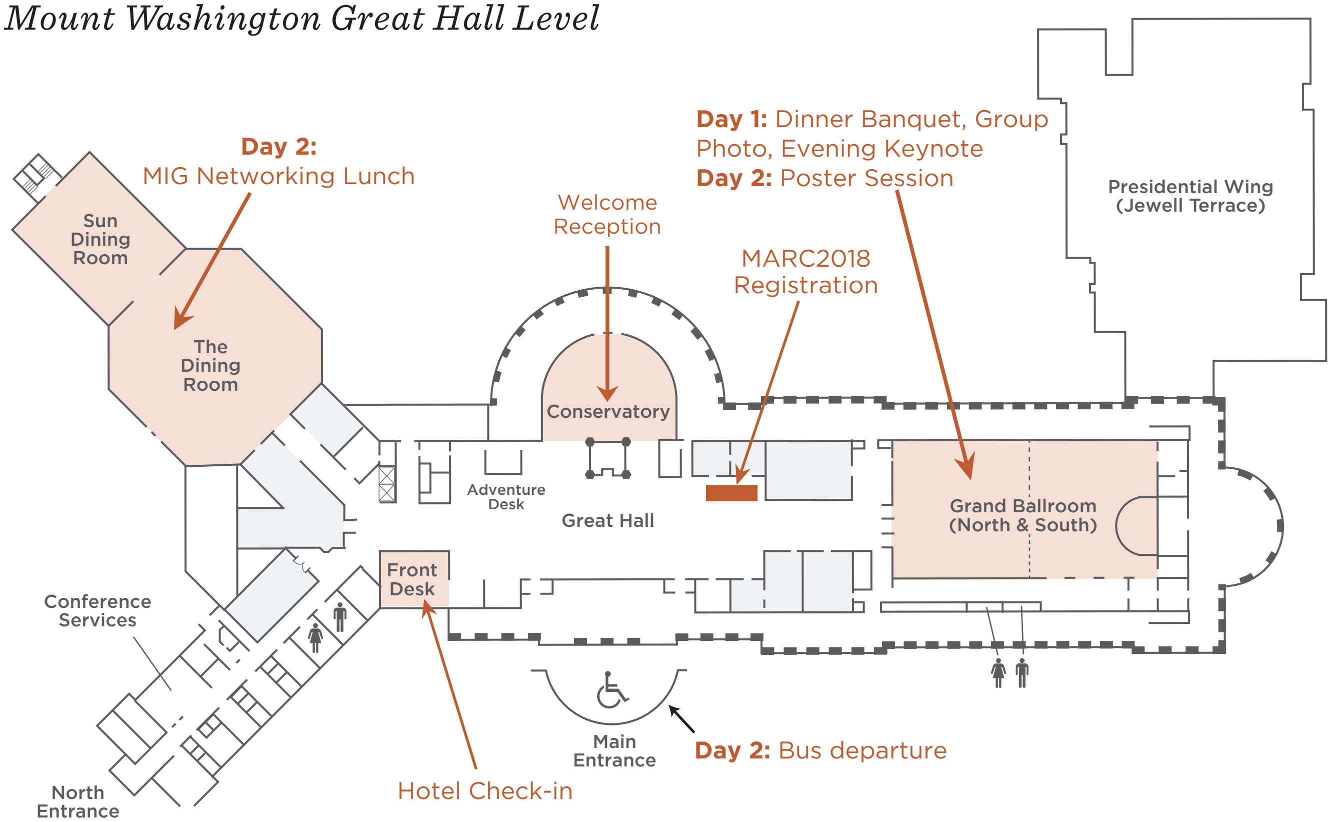
Most fiber-coupled surgical lasers used to remove biological tissue do so via photothermal excitation, wherein the photon energy is translated into thermal energy in the tissue via absorption by the resident water. Though selecting water as the chromophore has the advantage of being applicable to removing a wide range of tissues, it has some limitations, particularly when operating adjacent to very sensitive tissue types such as neural elements. Some limitations are due to the present day implementation, and some are due to the employed ablation mechanism as determined by the laser pulse width, amplitude, and wavelength.

With regard to the implementation, as the delivery fiber is typically multimode and has a relatively high numerical aperture, the beam diverges quickly as it exits the fiber. As a result, for a given laser pulse energy, the "cutting power" of the laser can vary drastically as a function of small changes in distance to the target tissue. Therefore, the laser may be perceived by the user (i.e. surgeon) as being imprecise. In addition, the spatial and temporal beam-shape out of the laser fiber is not optimized to minimize collateral thermal damage by minimizing the deposition of "non-useful" energy, which translates to temperature rise adequate to kill tissue, but not remove it. With regard to laser wavelength, ablation is achieved by heating water in the tissue, which is not always the most energy-efficient path to ablation and results in significant thermal damage to adjacent tissue. This research will explore delivery systems and ablation mechanisms optimized to ablate target tissue with minimal disruption to adjacent tissue, resulting in a more precise, more useful surgical instrument.

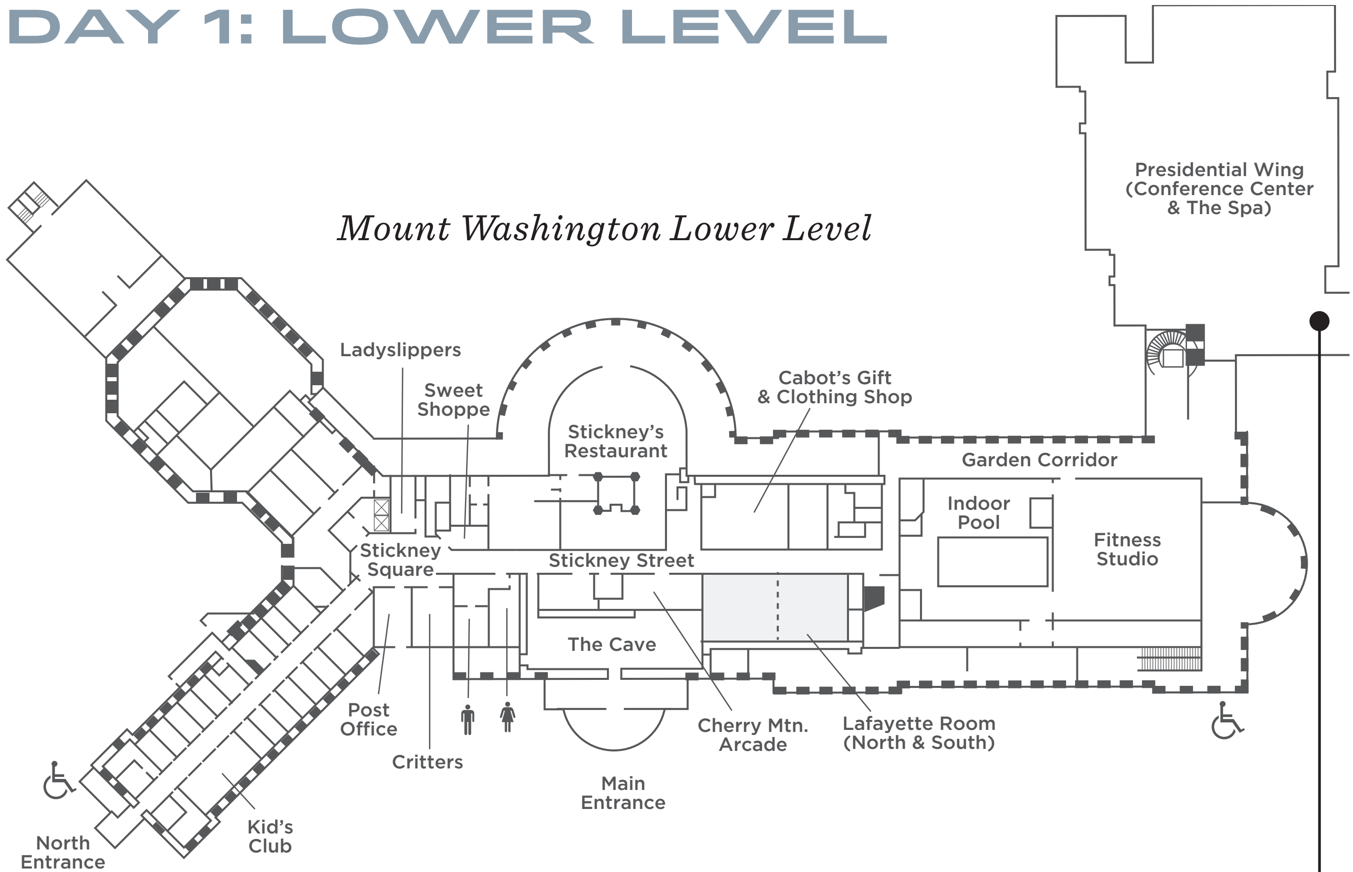
MAPS

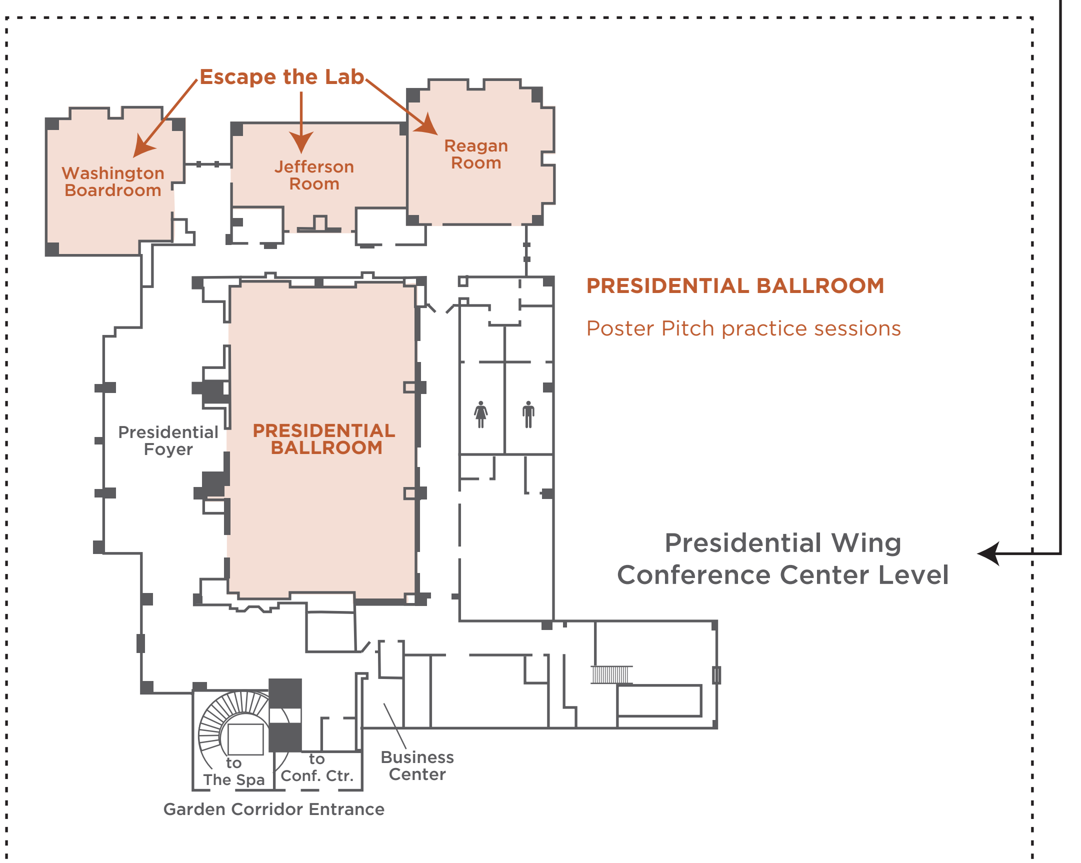


Mount Washington Great Hall Level



DAY 1: LOWER LEVEL





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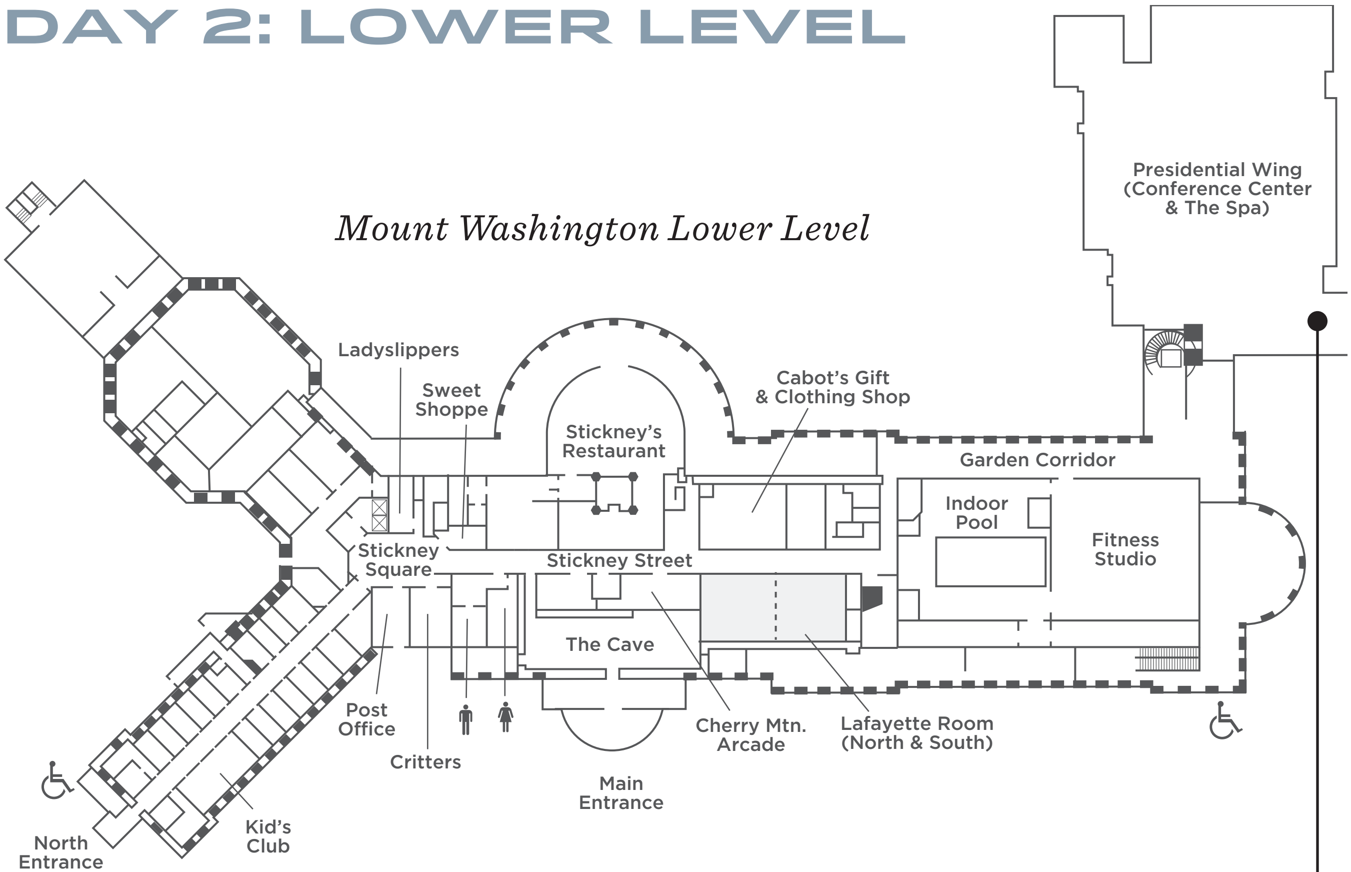

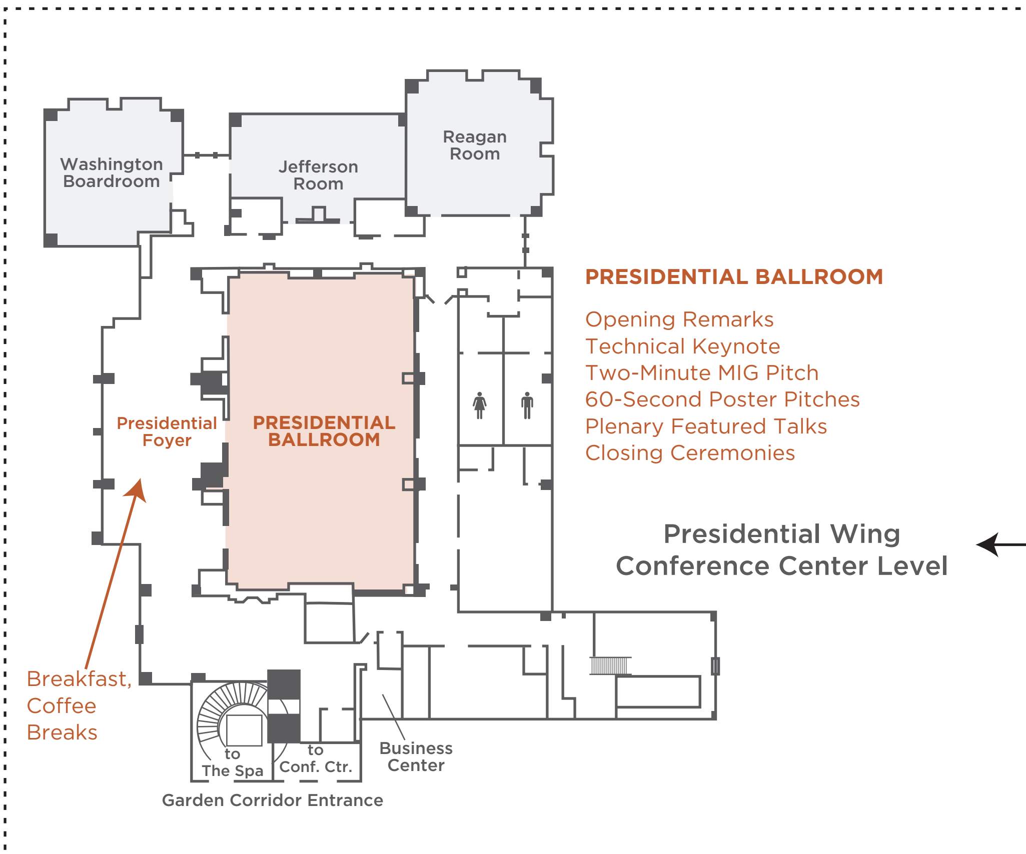

PRESIDENTIAL BALLROOM

Opening Remarks
Technical Keynote
Two-Minute MIG Pitch
60-Second Poster Pitches
Plenary Featured Talks
Closing Ceremonies

AUTHOR INDEX