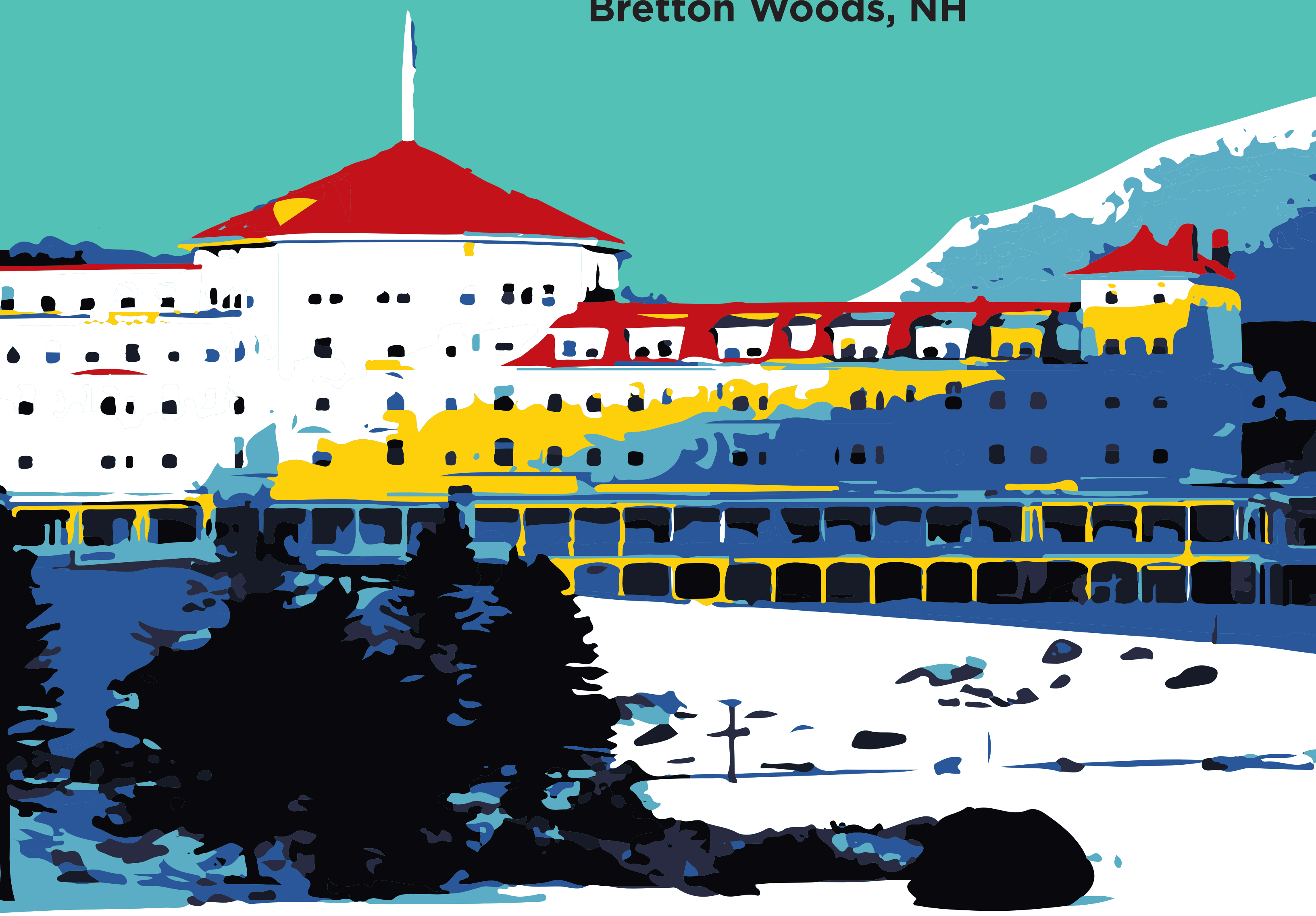
MICROSYSTEMS TECHNOLOGY LABORATORIES • MICROSYSTEMS ANNUAL RESEARCH CONFERENCE

MARC 2017

CONFERENCE PROCEEDINGS

January 31–February 1, 2017
Bretton Woods, NH



Massachusetts Institute of Technology

MTL EXPO

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INTRODUCTION

A warm welcome to MARC2017: Microsystems Annual Research Conference of MTL (Microsystems Technology Laboratories)! Since its inception as the "MTL Annual Student Review" in 1984, MARC has evolved into a student-led conference that brings together MTL-affiliated students, postdocs, faculty, as well as industrial partners.

This year, MARC2017 is part of a week-long series of events at MTL that we call MTL EXPO. It includes the annual meeting of the Industrial Advisory Board (IAB2017), and a new event showcasing recent startups that have roots in MTL (StartUp@MTL 2017), in addition to MARC.

We are delighted to be back in the mountains of New Hampshire, at the Omni Mount Washington Resort for MARC2017, and to celebrate the innovations and accomplishments of MTL. MARC strives to be the platform for showcasing MTL research, networking opportunities, and a host of fun winter activities.

Following the first day of winter activities in Bretton Woods, MARC2017 starts with an evening reception, featuring a dinner panel discussion. The panel, "The MTL Launchpad: Perspectives from Alumni in Academia, Startups, and Industry," promises to provide candid career insights.

The technical portion of MARC2017 begins with the morning keynote by Professor Vladmir Bulović, Associate Dean for Innovation at MIT. He is the leading faculty for the design and construction of MIT.nano. The world-class research facility promises to accelerate the pace of nanotechnology research. His talk, "The Future will be Measured in Nanometers," will provide a vision for the future of material and device research and how MIT.nano can address the emerging technological challenges.

The keynote speech will be followed by short presentations by MTL industrial group members (MIG) members. MIG pitches are a new addition to MARC, which aim to demonstrate state-of-the-art technologies in industry and to inspire conversations between MTL researchers and MIG members.

MARC2017 showcases over 100 abstracts from 40 MIT research groups, representing the impressive research diversity in MTL. As a MARC tradition, each abstract will be paired with a short presentation in 7 broad research themes: Electronic & Quantum Devices, Circuits & Systems, Nanotechnology & Nanomaterials, MEMS & NEMS, Energy, Photonics & Optoelectronics, and Biological & Medical Devices. Select abstracts from MTL students and postdoctoral researchers will be presented as 15-minute feature talks, in three parallel sessions. We encourage you to further explore topics of interest through visiting the poster presentations and technical demos.

We are confident that the knowledge, perspectives, and anecdotes shared in MARC2017 will resonate strongly amongst us and spark new ideas and conversations. On behalf of the MARC2017 organizing committee, we would like to thank all the participants—you make this unique conference possible. We want to express our gratitude to the MTL director, Professor Jesús del Alamo, for his leadership and support. We are extremely grateful for the support from the administration staff and student volunteers. Finally, we thank you for coming to MARC2017. We hope you enjoy your time with us in Mount Washington!

Sincerely,
Xiaowei Cai, Ujwal Radhakrishna, and the MARC2017 Organizing Committee

AGENDA

DAY 1: JANUARY 31

7:00 am	**Early Bus Departs MIT** 84 Mass. Ave, Cambridge
10:00 am–3:30 pm	**Winter Activities** Bretton Woods, NH Many things have been planned for our attendees, from skiing on Mount Washington to indoor activities. Activities will only be available for attendees arriving on the early bus (or those coming by private transportation).
Noon	**Late Bus Departs MIT** 84 Mass. Ave, Cambridge
3:00 pm–4:00 pm	**Hotel Tour** Omni Mt. Washington Resort Optional for those arriving on the noon bus from MIT.
4:00 pm–5:00 pm	**Check-in** Great Hall
5:00 pm–6:00 pm	**Welcome Reception** Conservatory
6:00 pm–7:30 pm	**Dinner Banquet** Grand Ballroom
7:30 pm–8:30 pm	**Evening Panel Discussion** Grand Ballroom "The MTL Launchpad: Perspectives from Alumni in Academia, Startups, and Industry," moderated by Dr. Phillip Nadeau.
8:30 pm–Midnight	**Evening Activities** Monroe, Madison, and Adams Rooms Various group activities planned for the enjoyment and participation of all attendees, including the return of "Escape the Lab."

DAY 2: FEBRUARY 1

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 MARC2017 co-chairs, Xiaowei Cai and Ujwal Radhakrishna.
8:15 am–8:45 am	**Technical Keynote** Presidential Ballroom "The Future will be Measured in Nanometers," Vladimir Bulović
8:45 am–9:15 am	**Two-Minute Pitch from MIG Members** Presidential Ballroom
9:15 am–10:00 am	**60-Second Poster Pitch, Session 1** Presidential Ballroom
10:00 am–10:15 am	**Coffee Break** Presidential Foyer
10:15 am–11:30 am	**60-Second Poster Pitch, Session 2** Presidential Ballroom
11:30 am–Noon	**Group Photo** Grand Staircase
Noon–1:00 pm	**MIG Networking Lunch** Dining Room
1:00 pm–2:00 pm	**Poster Session 1** Grand Ballroom
2:00 pm–2:15 pm	**Coffee Break** Presidential Foyer
2:15 pm–3:00 pm	**Featured Talk Tracks I-III** Monroe, Madison, and Adams Rooms Three parallel sets of featured talks chosen from abstracts submitted by the student and postdoc poster presenters to take place in the Monroe, Madison, and Adams rooms.
3:00 pm–4:00 pm	**Poster Session 2** Grand Ballroom
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.

EVENING PANEL DISCUSSION

"The MTL Launchpad: Perspectives from Alumni in Academia, Startups, and Industry"

ACADEMIA, INDUSTRY

VIVIENNE SZE

Assistant Professor
MIT

Vivienne Sze is an assistant professor in the EECS Department at MIT. Her research interests include energy-aware signal processing algorithms and low-power circuit and system design for multimedia applications. Prior to joining MIT, she was a member of technical staff in the R&D Center at Texas Instruments, where she developed algorithms and hardware for the latest video coding standard H.265/HEVC.

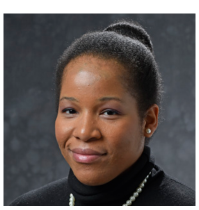
Prof. Sze received the B.A.Sc degree from the University of Toronto in 2004, and the S.M. and Ph.D. degrees from MIT in 2006 and 2010, respectively. She is a recipient of the 2016 AFOSR Young Investigator Award, the 2014 DARPA Young Faculty Award, and the 2011 Jin-Au Kong Outstanding Doctoral Thesis Prize.

ACADEMIA

JAMES TEHERANI

Assistant Professor
Columbia University

James Teherani joined Columbia University as an assistant professor in the Department of Electrical Engineering in 2015. He received his B.S. in electrical and computer engineering from the University of Texas at Austin in 2008, and his S.M. and Ph.D. degrees in electrical engineering and computer science from the Massachusetts Institute of Technology in 2010 and 2015. His research interests include the fabrication, characterization, and quantum-mechanical modeling of electronic devices, quantum structures, and emerging materials, especially 2D semiconductors. He was a co-recipient of the 2014 George E. Smith Award for best paper in IEEE Electron Device Letters for his work on record-high hole mobility in strained-Ge MOSFETs.



GOVERNMENT LAB, INDUSTRY

MELISSA SMITH

Technical Staff
MIT Lincoln Laboratory

Melissa Smith is a technical staff member in the Chemical, Microsystem, and Nanoscale Technologies Group at Lincoln Laboratory, where she is exploring new methods and strategies to build integrated microfabricated devices that are highly scalable. In addition to these activities, her broader interests include semiconductor materials and devices for flexible MEMS and other large area applications. Prior to joining the Laboratory, Dr. Smith worked at IBM Microelectronics, where she worked in process development for epitaxial thin films. In addition, she has industry experience in materials testing, characterization, and processing through internships at Deere & Company, 3M, and Xerox Corporation. Dr. Smith received her Ph.D. in materials science and engineering from the Massachusetts Institute of Technology and her B.S. in materials science and engineering from the University of Illinois at Urbana-Champaign.

INDUSTRY, STARTUP

JOYCE WU

System Engineer
Analog Garage

Joyce Wu graduated from MIT with a Ph.D. in Electrical Engineering researching 3-D interconnects with Prof. Jesús del Alamo. She joined the startup Pixtronix, a MEMS-based display company based in Andover, MA, in 2007 as a MEMS designer. Pixtronix was acquired by Qualcomm in 2011 while they were developing their first product with Sharp. Currently, she is a System Engineer in the Analog Garage, a startup-driven division of Analog Devices, Inc., in Cambridge, MA, that brings new technologies to market.

STARTUP

LOUIS PERNA

Founder & Lead Mechanical Engineer
Accion Systems

Louis Perna is a co-founder of Accion Systems Inc., a provider of high-performance electric micropropulsion for spacecraft, where he focuses on product development, manufacturing, testing, and research. He received his bachelor's and master's degrees from the MIT Department of Aeronautics and Astronautics where he specialized in space propulsion, specifically microsystems design and manufacturing for electrospray thrusters. Louis has supported various NASA centers both academically and professionally including investigating ion engine operating modes; design, test, and assembly of planetary exploration robotics systems; and program- and vehicle-level technical and programmatic risk estimation for manned spaceflight systems.

MODERATOR

PHILLIP NADEAU

Postdoctoral Associate
MIT

Phillip Nadeau is a postdoctoral associate in MTL at MIT, working on energy-efficient integrated circuit/system design in Professor Anantha Chandrakasan's research group. He received the S.M. and Ph.D. in EECS from MIT in 2011, and 2016 respectively, and the B.A.Sc. in Electrical Engineering from the University of Waterloo, Canada in 2009, His research interests are in the areas of RF and medical devices and systems. He served as MARC Co-Chair in 2014. He has previously interned at Texas Instruments (2014, 2012) and Intel (2011). He was a recipient of the Qualcomm Innovation fellowship (2014), the Harold L. Hazen Teaching award at MIT (2012), the Natural Sciences and Engineering Council of Canada post-graduate fellowship (2012 and 2009), and the Governor General of Canada's Academic Medal (2009).

TECHNICAL KEYNOTE

"The Future will be Measured in Nanometers"

VLADIMIR BULOVIĆ

Associate Dean for Innovation, MIT School of Engineering
Professor of Engineering, MacVicar Fellow
Fariborz Maseeh (1990) Chair in Emerging Technology
MIT

Vladimir Bulović is the Associate Dean for Innovation in MIT's School of Engineering, overseeing a broad portfolio of efforts that support innovation and entrepreneurship. He co-directs the campus-wide MIT Innovation Initiative and is the faculty leading the design and construction of MIT.nano, MIT's new nano-fabrication, nano-characterization, and prototyping facility. Bulović is a Professor of Electrical Engineering, holding the Fariborz Maseeh Chair in Emerging Technology. He leads the Organic and Nanostructured Electronics laboratory and co-directs the MIT-ENI Solar Frontiers Center and the MIT Energy Initiative's Low Carbon Energy Center on Solar technologies.

Bulović's research interests include studies of physical properties of organic and organic/inorganic nanocrystal composite thin films and structures, and development of novel nanostructured optoelectronic devices. He is an author of over 250 research articles (cited over 30,000 times) and an inventor of over 90 U.S. patents in areas of light emitting diodes, lasers, photovoltaics, photodetectors, chemical sensors, programmable memories, and micro-electro machines, majority of which have been licensed and utilized by both start-up and multinational companies. The three start-up companies Bulović and his students co-founded jointly employ over 300 people, and include QD Vision, Inc. of Lexington MA, producing quantum dot optoelectronic components (acquired by Samsung in 2016); of Kateeva, Inc. of Menlo Park CA, focused on development of printed organic electronics; and Ubiquitous Energy, Inc., developing nanostructured solar technologies.

Bulović received his Ph.D. from Princeton University, where his academic work and patents contributed to the launch of the Universal Display Corporation and the Global Photonics Energy Corporation. He is a recipient of the U.S. Presidential Early Career Award for Scientist and Engineers, the National Science Foundation Career Award, the Ruth and Joel Spira Award, Eta Kappa Nu Honor Society Award, and the Bose Award for Distinguished Teaching. Recognized as an authority in the field of applied nanotechnology, Bulović was named to the Technology Review TR100 List, and in 2012 he shared the SEMI Award for North America in recognition of his contribution to commercialization of quantum dot technology.

In 2008, he was named the Class of 1960 Faculty Fellow, honoring his contribution to energy education, which led to the launch of the MIT Energy Studies minor, the first academic program that spans all five schools at MIT. In 2016 he co-led the launch of the MIT Entrepreneurship and Innovation minor, which is also designed to be accessible to all MIT students. In 2009, Bulović was awarded the Margaret MacVicar Faculty Fellowship, MIT's highest teaching honor, and in 2011 he was named the Faculty Research Innovation Fellow for excellence in research and international recognition. Recently, Bulović was named the Xerox Distinguished Lecturer in recognition for his continued contribution to innovation of practical applied nanotechnologies.

MIG MEMBER COMPANIES

Analog Devices, Inc.
Applied Materials
Draper
DSM
Edwards Vacuum
Foxconn Electronics
HARTING
Hitachi High-Technologies
Intel
IBM
Lam Research Co.
NEC
Qualcomm
Samsung
STMicroelectronics
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. For the first time this year at MARC2017, MIG members are invited to give two-minute pitches about activities at their respective companies.

FEATURED TALKS

TRACK I MONROE ROOM

III-V Vertical Nanowire Transistors for Ultra-Low Power Applications
Xin Zhao

Microfabrication-Based Technologies for Large-Scale Recording of Neural Activity in the Brain
Jorg Scholvin

TRACK II MADISON ROOM

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

Ultra Low-Power, High-Sensitivity Secure Wake-Up Transceiver for the Internet of Things
Mohamed Radwan Abdelhamid

TRACK III ADAMS ROOM

Conformal Electroplating of Azobenzene-Based Solar Thermal Fuels onto Large Area & Fiber Geometries
David Zhitomirsky

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Xiaowei Cai
(x_cai@mit.edu)
Seeking summer internship.
PhD advised by Jesús del Alamo.
Available from June 2018.

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

F-induced Electrical Instability in Self-aligned InGaAs MOSFETs

1.01

X. Cai, J. Lin, D. A. Antoniadis, J. A. del Alamo
Sponsorship: DTRA, Lam Research Corporation

InGaAs has merged as a promising n-channel material candidate for future nano-scale CMOS thanks to its low voltage operation and superior electron transport properties. While the process technology and performance of InGaAs MOSFETs continues to improve, there is an increasing concern regarding the electrical reliability of this device technology, due to reactive ion etching (RIE) damage, ion contamination, radiation damage etc.

We have observed, for the first time, a prominent but fully reversible enhancement in peak transconductance after applying positive gate stress to self-aligned InGaAs MOSFETs. We attribute this to electric-field induced migration of Fluorine (F), introduced during the RIE gate recess process. We confirm F contamination in our process through secondary ion mass spectroscopy (SIMS), and F induced donor passivation through transmission line model (TLM) structures. We have successfully eliminated this instability by eliminating n-InAlAs from the device structure. The new device design achieves improved stability and record device performance.

Dongsung Choi
(dschoi@mit.edu)
Seeking summer internship.
PhD advised by Jesús del Alamo.
Available from February 2017.

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

Analysis of Mo Sidewall Ohmic Contacts to InGaAs Fins

1.02

D. Choi, A. Vardi, J. A. del Alamo
Sponsorship: DTRA, Lam Research, E3S, ILJU Academy and Culture Foundation

Continued progress with Moore's law will soon bring us to sub-10 nm CMOS technology nodes. To accomplish this, InGaAs as a new channel material and novel vertical transistor structures are looking very promising. In vertical transistor structures, such as the vertical nanowire MOSFET, metal contacts not only cover the top surface of the device, but also wrap around the sidewalls. For this reason, it is imperative to study sidewall ohmic contacts. To date, there has not been an investigation on sidewall contacts for InGaAs vertical structures to the best of our knowledge.

This study aims to extract Mo/n^+-InGaAs sidewall contact resistance and investigate ways to improve it. Toward this goal, we have fabricated transmission-line model structures using InGaAs fins with Mo/n^+-InGaAs sidewall contacts. To achieve this, we leave the etch mask on the fins and deposit conformal Mo around them. From these structures, we extract a sidewall contact resistivity of $6.5\pm0.4\ \Omega\cdot\mu m^2$ (single-cycle digital etch of the fins with HCl, no annealing). To improve contact resistivity, we have explored the effect of digital etch of the sidewalls prior to Mo deposition and final thermal annealing on the sidewall contact resistivity. Digital etch using H_2SO_4 and HCl have been found to have a weak effect on the sidewall contact resistivity. However, upon annealing under optimum conditions, a contact resistivity as small as $3.6\ \Omega\cdot\mu m^2$ has been obtained. While this is an excellent result, future vertical transistors will require a sidewall contact resistivity about a factor of 10 times smaller than this.

Spin-Orbit Torque Efficiency in Compensated Ferrimagnetic Cobalt-Terbium Alloys

1.03

J. Finley, L. Liu
Sponsorship: NSF-SRC

There has been great interest recently in using antiferromagnetically coupled materials as opposed to ferromagnetic materials (FM) to store information. Compared with FM, antiferromagnetically coupled systems exhibit fast dynamics, as well as immunities against perturbations from external magnetic fields, potentially enabling spintronic devices with higher speed and density. Despite the potential advantages of information storage in antiferromagnetically coupled materials, it remains unclear whether one can control the magnetic moment orientation efficiently because of the cancelled magnetic moment.

Here, we report spin-orbit torque induced magnetization switching of ferrimagnetic $Co_{1-x}Tb_x$ films with perpendicular magnetic anisotropy. By varying the relative concentrations of the two species, one can reach compensation points where the net magnetic moment or angular momentum goes to zero. We demonstrate current induced switching in all of the studied film compositions, including those near the magnetization compensation point. We then quantify the spin-orbit torque induced effective field in the domain wall motion regime, where we find that close to the compensation point, a divergent behavior that scales with the inverse of magnetization, which is consistent with angular momentum conservation. Moreover, we also quantified the Dzyaloshinskii-Moriya interaction energy in the $Ta/Co_{1-x}Tb_x$ system, and we found that the energy density increases as a function of the Tb concentration. This tunable DMI could be potentially useful for spintronic applications that employ stable magnetic textures such as skyrmions and chiral domain walls. The large effective spin-orbit torque, the previously demonstrated fast dynamics, and the minimal net magnetization in these ferrimagnetic systems promise spintronic devices that are faster and with higher density than traditional ferromagnetic systems.

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Novel Device Design for High Linearity GaN Power Amplifier

1.04

J. Hu, D. Piedra, U. Radhakrishna, J. Grajal, T. Palacios
Sponsorship: RUAG

Gallium Nitride (GaN)-based high-electron-mobility transistor (HEMT) has been an emerging technology for the use in next-generation wireless communication systems. The combination of high electron mobility and critical electric field allows unprecedented power level, power-added-efficiency (PAE) and breakdown voltage in GaN power amplifiers (PAs). Despite the advances in GaN RF technology, the non-linearity characteristics of GaN PAs and the impact on the circuit performance have not been thoroughly investigated.

The goal of this project is to understand the key device design parameters and their impact on the amplifier linearity, to improve the g_m and f_T linearity characteristics of GaN PAs by means of device-level and thermal design without compromising the aforementioned figures of merits (FOMs).

From the results based on the MIT Virtual Source GaNFET-RF (MVSG) model, we understand that the primary non-linear content in g_m occurs in the region of transition from weak to strong accumulation. This causes significant higher order harmonic components and intermodulation distortion (IMD) in power amplification. To solve this problem, we are proposing several new approaches to engineer the transition between weak and strong accumulation in GaN multi-finger power amplifiers. In this way, we are able to tailor the overall transconductance characteristics to attenuate the higher order transconductance and minimize the IMD.

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High Linearity GaN-transistors for RF and High Power Amplification

1.05

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Sponsorship: RUAG, Office of Naval Research PECASE Program

The recent proliferation of mobile devices along with the surge in the demand for Internet of Things (IoT) is promoting the need for efficient wireless data communication. Key emergent applications ranging from 5G-LTE, WIMAX, Sat-Com, CAT-TV, radar, space applications, D2D, and other communication protocols in the range of L-band to millimeter-wave have to operate within the stringent constraints on the spectral bandwidth as well as adjacent-channel interference. In addition, the base station accounts for 56% of the total power consumed in a typical end-to-end cellular network and the RF power amplifier (PA) in the base station contributes a significant portion of this power budget. As a result, there is a strong need to achieve high-linearity high-efficiency PAs to avoid intermodulation distortion and channel interference.

In this work, we exploit the properties of the AlGaN/GaN heterostructure system, along with a new device architecture to attain device-level implementation of high linearity. The proposed device is based on a nano-wire (NW) structure. Numerous NWs with varying width form the channel of the transistor and are connected in parallel to form the device. In comparison to a planar AlGaN/GaN transistor of the same effective width, the NW-GaNFET displays a lower g_m'' (double derivative of transconductance, an important measure of linearity). In addition, large signal linearity improvement has been demonstrated in these NW based devices. Also, for Class-B configuration, the power added efficiency is shown to be higher than a planar AlGaN/GaN transistor. Simultaneously, power output at the harmonic frequencies is lower and the intermodulation distortion is reduced. In conclusion, high linearity in GaN transistors is obtained by a new architecture at the device level.

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Improving the High-k Gate Dielectric Interface in III-V FinFETs

1.06

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

Sponsorship: UROP, Lam Research

In III-V Fin Field-Effect Transistors (FinFETs), the interface between the channel material, such as InGaSb or InGaAs, and the high-k gate dielectric plays a critical role in electrical performance. Properties of interest include defect density, interdiffusion between the semiconductor and dielectric, as well as roughness of the dielectric-semiconductor interface. Using high-resolution transmission electron microscopy (HRTEM), we can directly study this interface and understand how it is affected by different processing conditions and its correlation with device characteristics. A preliminary analysis of an InGaSb p-channel FinFET displayed inadequate gate control of the channel current. TEM images revealed a non-uniform Al_2O_3 gate dielectric as well as interdiffusion between InGaSb and the Al_2O_3. To improve this interface, we are exploring methods of passivation of the InGaSb surface before Al_2O_3 deposition, as well as methods to improve the quality of the Al_2O_3 layer. To characterize and compare our devices, we are studying correlations between capacitance-voltage (C-V) measurements and HRTEM cross sections. We will present processing methods found to improve interfacial properties and device performance.

Time-Dependent Dielectric Breakdown in High-Voltage GaN MIS-HEMTs: The Role of Temperature

1.07

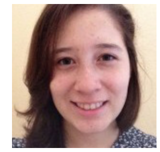
A. Lemus, S. Warnock, J. A. del Alamo

Sponsorship: Texas Instruments

There is a large demand for energy-efficient power electronics, for which silicon-based devices – “the current market standard” – are not ideal. GaN, however, has material properties such as its large band gap of 3.4 eV that are well-suited for power efficiency. GaN-based transistors offer a promising solution for these applications, but there are still several reliability challenges that remain. The motivation of our work is to address a specific reliability challenge and failure known as time-dependent dielectric breakdown (TDDB). We study GaN Metal-Insulator-Semiconductor High Electron Mobility Transistors (MIS-HEMTs), which have a lower gate leakage than HEMTs that is necessary for power switches.

TDDB is a catastrophic event that occurs in devices under prolonged high-voltage gate bias stress. This results in defect formation in the device dielectric, which facilitates current flow between the gate and its conductive channel. Eventually, a highly conductive path will form in the dielectric and the instantaneous power dissipation through that path creates a short through the dielectric, consequentially destroying the device. Our interest is to explore the origin of TDDB mechanism in GaN devices and how it is affected by temperature.

We choose to conduct our TDDB experiments at several different temperatures for constant positive gate voltage stress. We observe a negative correlation between temperature and the breakdown time of our devices. We were also able to identify a shallow activation energy for TDDB in these devices which is smaller than other reported values in the GaN MIS-HEMT system. This research ultimately aims to contribute to the understanding of TDDB in GaN MIS-HEMTs towards the goal of developing a TDDB lifetime model.



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A High-Purity Single Photon Emitter in Aluminum Nitride

1.08

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Sponsorship: U.S. Army Research Laboratory, Air Force Office of Scientific Research

Efficient, on-demand, and robust single photon emitters (SPEs) are essential to many areas of quantum information processing. Over the past decade, color centers in solids have emerged as excellent SPEs and have also been shown to provide optical access to internal spin states. Color centers in diamond and silicon carbide are among the most intensively studied SPEs. Recently, other cost-efficient wide-bandgap materials have become attractive as potential host materials. Theoretical calculations show that aluminum nitride (AlN) with a bandgap of 6.015 eV can serve as a stable environment for well isolated SPEs with optically accessible spin states.

Here, we report on a room-temperature SPE that emits in the visible spectrum. The SPEs are hosted by AlN thin-films on sapphire substrates. Annealing treatments enable the control of their photostability and visibility. These SPEs are highly efficient and emit single photons up to 95% purity and enable photon count rates up to 1 million counts per second at saturation while persisting a high single photon purity. The presence of high-purity SPEs, along with the good optomechanical properties, makes AlN a promising candidate for quantum information processing.

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Digital Etch for Sub-10 nm III-V Multigate MOSFETs

1.09

W. Lu, X. Zhao, J. A. del Alamo
Sponsorship: DTRA, KIST, Lam Research, NSF, Samsung

As CMOS technology keeps advancing, new materials are under active research in the hope of replacing Si in future generations. III-V multi-gate transistors such as InGaAs FinFETs or nanowire gate-all-around MOSFETs are regarded as some of the most promising candidates. As the physical size of Si FinFETs is shrinking, it is critical to develop the technology to fabricate III-V 3-D devices in the sub-10 nm range. In this dimensional regime, precise etching control is the key challenge.

In this project, we have developed a novel non-aqueous digital etch technique which enables the fabrication of sub-10 nm vertical fins and nanowires. The new approach uses acids dissolved in alcohol, which has less surface tension than water and, therefore, exerts smaller mechanical forces against the nanowires. We obtain a consistent 1 nm/cycle etching rate on both InGaAs and InGaSb-based heterostructures. We show an over 97% yield in the fabrication of sub-10 nm vertical nanowires. We have also demonstrated a record 5 nm diameter nanowire with a height of 230 nm and an aspect ratio of 46. Finally, we fabricated InGaAs vertical single nanowire MOSFETs using this technique. Those transistors have a linear subthreshold swing of 70 mV/dec, one of the best values reported in such devices. This shows that the new digital etch technique is effective in yielding a high quality surface in InGaAs nanowires. We are now working towards applying this technique to demonstrate InGaAs and InGaSb FinFETs and nanowire MOSFETs with sub-10 nm fin width and nanowire diameter.

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Characterizing Single Photon Emitters in GaN

1.10

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Sponsorship: MIT SuperUROP, Texas Instruments

A recently discovered class of defects in GaN could provide exciting opportunities for implementing solid-state qubits. These defects can act as single photon emitters (SPEs) and are appealing due to the flexibility that GaN can provide in device fabrication. Photoluminescence measurements have shown high intensity with zero phonon lines over a wide range of wavelengths. Despite this broad spectrum, we believe many of these defects arise from the same point defect with differences in zero phonon lines occurring due to strain from dislocations in the lattice.

To further understand GaN SPEs, we use a combined experimental and computational approach. We use cathodoluminescence microscopy to determine variations in the structure and chemical composition of defects. We also plan on measuring the strain dependence of zero phonon lines to determine the role of lattice strain on photoluminescence and the number of unique point defects detected. Experimental data from these studies will allow us to use density functional theory with the LDA-1/2 method to obtain defect level energies and transition energies. We will then compare transition energies with experimental data to validate the method's accuracy and use the results to determine the feasibility of implementing qubits with these defects.

Demonstration of AlN Transistors

1.11

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Sponsorship: JSPS

Hybrid-electric and full-electric vehicles have rapidly developed to solve the air pollution and global warming by hydrocarbon combustion. These electric vehicles require DC-DC converters for the energy transfer between high voltage batteries, which run motors, and low voltage ones, which recharge the batteries and supply the power to electric components. Silicon-based power devices are now used for the DC-DC converters. DC-DC converters using wide-band gap semiconductors, like silicon carbide (SiC) and gallium nitride (GaN), would allow for less energy consumption and the miniaturization of the power units. SiC DC-DC converters are already at the testing stage for hybrid-electric vehicles, confirming the improvement of fuel efficiency. Comparing with SiC and GaN, aluminum nitride (AlN) has the highest breakdown field of 15 MV/cm. This means that AlN-based devices allow higher doping for a given high-voltage application, leading to lower resistance at the ON status, or higher energy efficiency.

Undoped AlN films with dislocation densities of ~10^9 cm^{-2} are commercially available. N- and p-type conductivity is achieved by Si and Mg doping, respectively. However, the reports on AlN electric devices are limited to Schottky-barrier diodes, because AlN suffers from high contact resistivity (>10^{-2} Ohm cm^2) and low carrier concentrations due to high potential-barrier height at a metal/AlN interface and large ionization-impurity energy (> 0.3 eV). The demonstration of AlN-based switching devices is very challenging but could also be very impactful. In this project, we aim at demonstrating the first AlN transistors.

Information Limit of Domain Wall Based Nanowire Devices

1.12

S. Siddiqui, S. Dutta, J. A. Currivan-Incorvia, C. Ross, M. A. Baldo

Sponsorship: National Science Foundation

Spintronic and magnetic devices use the spin of electrons instead of their charge to implement ultra-low-power logic and memory applications. In domain-wall-based magnetic devices, charge or spin currents move the boundary between different magnetic domains in a nanowire. Rather than flipping the orientation of the entire wire at once, this incremental approach improves the energy efficiency. Domain walls, however, can be pinned by the line edge roughness of nanowires, affecting the operation of the devices. Notches created by edge roughness comparable to the width of domain walls has been identified as the most effective pinning sites for domain walls, although the precise relation between the line edge roughness and domain wall pinning sites is unknown. Here, we show the autocorrelation of pinning sites with the line edge roughness in sub-100 nm wide Co wires. We have shown both experimentally and with simulation that the correlation length of edge roughness defines the effective pinning site distribution for domain walls in individual nanowires. Applying a self-affine model for the intrinsic roughness of fabricated edges, our result identifies the limit for information density in magnetic nanowires used in both domain-wall-based logic and memory devices.

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Sub-10 nm Fin Width Self-aligned InGaAs FinFETs

1.13

A. Vardi, J. A. del Alamo

Sponsorship: DTRA, Lam Research, E3S

InGaAs is a promising candidate as channel material for CMOS technologies beyond the 10 nm node. In this dimensional range, only high aspect-ratio (AR) 3D transistors with a fin or nanowire configuration can deliver the necessary performance. At the point of insertion, InGaAs FinFETs with sub-10 nm fin widths and steep sidewalls will be required. In this work, we leverage high-precision fin etching and a self-aligned design to demonstrate the most aggressively scaled InGaAs FinFETs to date that also displays outstanding electrical characteristics. For this, we have used a CMOS-compatible front-end process featuring reactive-ion etching and digital etch that yields high-aspect ratio InGaAs fins with smooth high quality sidewalls with highly scaled gate oxide. The electrical characteristics of a typical device with L_g = 30 nm and W_f =7 nm approach state of the art Si FinFET devices. Well-behaved characteristics and good sidewall control are demonstrated. The device R_{on} is 320 Ω·µm and a peak g_m of 900 S/µm is obtained at V_{DS} = 0.5 V.

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OFF-state TDDB in High-Voltage GaN MIS-HEMTs

1.14

S. Warnock, J. A. del Alamo

Sponsorship: Texas Instruments

With the promise of higher-frequency, higher-temperature, and more efficient operation, GaN-based transistors show enormous potential for high-voltage power management applications. The AlGaN/GaN Metal-Insulator-Semiconductor High Electron Mobility Transistor (MIS-HEMT) constitutes the most suitable device structure for power switches as it offers lower gate leakage than its HEMT counterpart. Though GaN devices show great promise, there are a number of reliability challenges left to address before they can achieve widespread commercial deployment. Time-dependent dielectric breakdown (TDDB), a catastrophic condition that arises after prolonged high-voltage gate stress, is a particularly important concern. Thus far, studies under positive gate bias stress have shown dielectric degradation behavior similar to that of silicon MOSFETs.

In this work, we explore TDDB under OFF-state conditions, that is, a negative gate bias is used to turn off the channel and a high positive bias is applied to the drain terminal. This is the most common state of a power switching transistor in a power management circuit. In the OFF state, there is a high electric field through the gate dielectric at the gate edge on the drain side. Under prolonged stress, this will inevitably result in dielectric defect formation and eventual dielectric breakdown. It is uncommon to think of TDDB under OFF-state conditions and though there is limited work on this for GaN HEMTs, this reliability concern in MIS-HEMTs has thus far been overlooked.

We show evidence of GaN MIS-HEMT failure after prolonged OFF-state stress through a TDDB mechanism. In order to study this, we present a new methodology based on UV light that separates pervasive trapping-related transient effects such as current collapse and threshold voltage (V_T) shift, from permanent dielectric degradation. We also show that trapping effects during stress cause significant overestimation of device breakdown voltage under OFF-state stress conditions.

A Diamond:H/MoO_3 MOSFET

1.15

Z. Yin, A. Vardi, J. A. del Alamo

Sponsorship: Bose Foundation, US-Israel Bilateral Science Foundation

This work targets the development of p-type hydrogenated-diamond (Diamond:H) MOSFETs based on MoO_3 as surface transfer doping layer deposited by atomic layer deposition (ALD). These transistors are of interest for future high-power, high-frequency applications based on single-crystal diamond. For the first time, we have successfully demonstrated well-controlled growth of composition-stoichiometric MoO_3 with Bis(t-butylimido)bis(dimethylamino) molybdenum(VI) ($C_{12}H_{30}MoN_4$) as Mo precursor and pure H_2O as O source in ALD. After MoO_3 deposition onto Diamond:H, the p-type characteristics of Diamond:H were partially deactivated. This was mitigated by means of rapid thermal annealing in a nitrogen environment in a relatively narrow process window. After RTA, the p-type behavior from Diamond:H/MoO_3 recovered to its original value. Hall measurements on the final structures have yielded a sheet hole concentration of 1.9×10^{13} cm^{-2} and a hole mobility of 22.4 cm^2/Vs. Following this, we deposited HfO_2 by ALD as gate dielectric. Diamond:H/MoO_3 p-MOSFETs were demonstrated with a drain-current ON-OFF ratio of five orders of magnitude and well saturated characteristics. This work shows that MoO_3-based surface transfer doping of Diamond:H has potential for future high power transistor applications.

III-V Vertical Nanowire Transistors for Ultra-Low Power Applications

1.16

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

Sponsorship: NSF Award #093951 (E3S STC), Lam Research, SRC

In the future, logic technology will be used for Internet of Things and mobile applications, and reducing transistor power consumption is of paramount importance. Beyond Si CMOS, transistor technologies based on III-V materials are widely considered as a leading solution to lower the power dissipation by enabling dramatic reduction in the transistor supply voltage. Vertical nanowire (VNW) transistor technology holds promise as the ultimately scalable device architecture and VNW MOSFETs have been predicted to offer significant advantages compared to their horizontal counterpart in terms of performance-power tradeoff. VNW transistor architecture also fully unleashes the advantage of III-V materials by enabling bandgap engineering along the transport direction, opening the door for tunnel-FETs (TFETs), a quantum device that potentially breaks the power limits of MOSFETs.

This work demonstrates InGaAs based VNW MOSFETs and TFETs fabricated via a top-down approach. Record performance has been achieved in our latest InGaAs VNW MOSFETs in terms of the trade-off between subthreshold and ON current. The performance improvement compared to an earlier generation of MOSFETs mainly comes from a much better oxide/semiconductor interface enabled by improved ALD chamber conditioning and rapid thermal annealing. Stemming from the same reasons, our latest VNW TFETs have also shown state-of-the-art performance, delivering room-temperature sub-thermal subthreshold swing over two order of magnitude of current. The current level of the steep slope region was also among the highest. The improved oxide/semiconductor interface also greatly suppressed the significant temperature dependence of our previous generation of TFETs, which was attributed to a tunnel-assisted generation process from a high concentration of interface traps. In our newest devices, the subthreshold swing appears to saturate at a very low level at low temperatures, highlighting the potential of the NW geometry.

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Ultra Low-Power, High-Sensitivity Secure Wake-Up Transceiver for the Internet of Things

2.01

M. R. Abdelhamid, A. P. Chandrakasan
Sponsorship: Delta Electronics

Nanopower Internet-of-Things (IoT) devices deployed in short-range personal health devices, home automation systems, and longer-range industrial monitoring systems all consume a large portion of energy on their wireless communication systems. However, the adoption of these devices in daily life routine requires a long battery lifetime or an energy-harvested operation. In this work, we propose protocol optimizations for sensor-node driven communications. For base-station driven communication, we propose to achieve power reduction through an ultra-low-power wake-up receiver with optimizations in the protocols as well as the circuit design.

Wireless protocols such as Bluetooth low energy (BLE) are optimized for short-length packets with small preambles and reduced header sizes. However, low duty-cycle performance in the default connected-mode of operation is limited by periodic beacons and the requirement that the low-power sensor node absorbs the timing uncertainties and associated guard time intervals. The analysis of a commercial BLE radio performance shows that the average total power is much higher than the standby power of the radio, which presents opportunities for significant power reduction through protocol optimization. On the wake-up receiver chain, the design can exploit different trade-offs in the protocol to reach a sub-μW average power consumption while maintaining the specifications by the base station. Therefore, the sensitivity/power trade-off of the receiver can be mitigated through an optimized protocol and system. Additionally, the tremendous growth of IoT devices allows open communication among all sorts of devices.

With such a huge amount of data flowing through the network, security becomes a critical issue. Hence, we propose a wake-up transceiver system with reconfigurable wake-up patterns. The transceiver incorporates a transmitter that provides small amounts of data sporadically upon request and creates a two-way communication channel for secure wake-ups and transmissions.

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Low-Power Security-Acceleration Core for the Internet of Things

2.02

U. Banerjee, C. Juvekar, A. P. Chandrakasan

The Internet of Things (IoT) has introduced a vision of an Internet where all computing and sensing devices are interconnected. Digitally connected devices are encroaching on every aspect of our lives, including our homes, cars, offices, and even our bodies. Researchers estimate that there will be over 40 billion wireless connected devices by 2020. On one hand, the IoT enables fundamentally new applications, but on the other, these devices are attractive targets for cybercriminals, thus making IoT security a major concern. According to a report on the state of IoT security in 2015, 90% of IoT devices have collected personal data, but 70% of them used unencrypted network services.

Most commercial IoT transceivers either have no security implementations in hardware or only support symmetric key primitives like Advanced Encryption Standard (AES). To achieve end-to- end security in IoT networks, public key algorithms, like elliptic curve cryptography (ECC) 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 propose to design low-power security-acceleration hardware that interfaces with a standard micro-processor and supports ECC for key exchange and digital signatures, along with standard cryptographic components like AES, thus alleviating the security and efficiency trade-off observed in embedded devices.

Our work also focuses on optimizing network security protocols for efficient implementation in embedded devices. Standard implementations of these protocols tend to have a large communication overhead, which becomes an additional concern for battery-powered or energy-harvesting IoT devices. Therefore, our proposed hardware can not only secure private data using low power cryptographic computations, but also reduce energy consumption of the RF transceiver.

A 0.36V 128Kb 6T SRAM with Energy-Efficient Dynamic Body-Biasing and Output Data Prediction in 28nm FDSOI

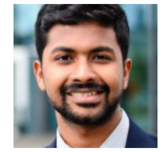
2.03

A. Biswas, A. P. Chandrakasan

Sponsorship: DARPA, STMicroelectronics

The aggressive scaling of SRAM bit-cell size with every technology node makes it extremely challenging to reduce the minimum supply voltage (Vdd,min) of SRAMs due to the increasing effect of device variations. However, Vdd scaling is crucial in reducing the energy consumption of SRAMs, which is a significant portion of the overall energy consumption in modern micro-processors. Energy savings in SRAM is particularly important for battery-operated applications, which run from a very constrained power-budget.

This work presents a low-voltage, energy-efficient SRAM designed in a 28nm fully depleted SOI (FDSOI) technology. The SRAM achieves a minimum Vdd of 0.36V, while still having the area advantage by using 6T bit-cells. Dynamic forward body-biasing (DFBB) is used to improve the write margin. The proposed implementation of DFBB provides a 4.5x improvement in energy overhead compared to a conventional implementation. It also helps in reducing the switching energy for half-selected bit-lines. An average energy/bit-access of 52.5fJ has been achieved at 0.45V. Furthermore, by implementing data prediction in the 6T read path, up to 36% dynamic energy savings can be obtained.



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Automatic Analysis of Traffic Behavior from Visual Surveillance of Intersections

2.04

J. Chen, S. Zhang, Y. Fang, I. Masaki, B. Horn

Sponsorship: Intelligent Transportation Research Center

Intelligent transportation system (ITS) plays an important role in public security, and automatic analysis of traffic behavior at intersection is one of the critical tasks in ITS. In this research, we present a novel system that detects traffic violations and abnormal traffic events from surveillance videos taken by cameras at intersections.

The system components include moving object segmentation, vehicle tracking, and behavior analysis, focused on surveillance of an intersection using videos from cameras aimed in specific directions. In moving object segmentation, we propose a temporal-spatial analysis based algorithm and also introduce the locations of the lanes to extract targets separately in each lane. Then, a modified kernelized correlation filter is used to track vehicles at high speed, without calibration.

We further detect specific traffic behaviors, such as speeding, lane changing and congestion for further analysis. We test our approaches in surveillance sequences, and the results show that the proposed framework is able to automatically detect specific traffic behaviors accurately in different intersection scenarios.

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

An Actively Detuned Wireless Power Receiver with Public Key Cryptographic Authentication and Dynamic Power Allocation

2.05

N. Desai, C. Juvekar, S. Chandak, A. P. Chandrakasan

Sponsorship: MIT Lincoln Laboratory, Texas Instruments

With the rapid growth in the number of devices with resonant wireless recharging capability, the number of chargers that are either counterfeit or not standards-compliant is expected to increase. These receivers must be protected from harsh transients imposed by such chargers. Additionally, single charger-multiple receiver scenarios are likely to become more commonplace. This makes it necessary to devise strategies to maintain equitable power distribution across all receivers irrespective of their physical placement with respect to the charger. Here, we present a wireless power receiver implemented in a 0.18um silicon process that addresses both these issues with a detuning technique that does not rely on any switched passives. The receiver can identify genuine chargers by using a public key-based authentication scheme built using Elliptic Curve Cryptography (ECC).

Each receiver contains two concentric coupled coils, a Main Coil that is used for receiving power during tuned operation and an Auxiliary Coil that controls the amount by which the receiver is detuned. The Auxiliary Coil is open-circuited during tuned operation, which allows the Main Coil to receive maximum power. To implement detuning, the load connected to the Auxiliary Coil is controlled using a duty cycle controller. This activates the feedback loop between the two coils on the receiver and displaces the receiver's poles that were previously aligned to the charger.

The receiver begins in the detuned state. Upon detecting the charger, it runs a public key challenge-response protocol using 163b-ECC, which offers a comparable level of security at lower cost compared to 1024b-RSA. After authenticating the charger, the power received in the tuned state can be increased up to 16 times that in the detuned state. In a scenario where two receivers are coupled to the same charger, detuning the closer receiver can reverse the skew in delivered power even with a 4:1 distance asymmetry.

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A Soft-Switched Power Converter for High Frequency and Density across Wide Operating Ranges

2.06

A. J. Hanson, R. S. Yang, S. Lim, D. J. Perreault

Sponsorship: ON (formerly Fairchild) Semiconductor

Power conversion circuits in all kinds of systems (telecommunications, consumer electronics, data centers, etc.) often represent a significant portion of total system volume and a bottleneck to both high overall efficiency and miniaturization. One way power converters can be made smaller is by increasing their operating frequency, but this only works if high frequency loss mechanisms can be controlled. One high frequency effect is "switching loss" which occurs when switches turn on and off. Since this occurs each cycle, the effect is more severe at higher frequencies.

Switching loss can be avoided through the use of "soft switching" which involves discharging switch voltages before turn-on, but this has only been widely achieved in applications with narrow operating ranges. Soft switching remains a challenge for applications with wide voltage/power ranges such as those which must interface with the ac grid.

In this project, we present a voltage step-up converter capable of achieving soft switching for any input voltage, allowing it to be operated efficiently at much higher frequencies to aid miniaturization. The converter presents further advantages over other soft-switched topologies, including low frequency variation, low circulating current, and low rms current. We demonstrate these advantages with a prototype which achieves soft switching across universal grid voltages at 1-5 MHz (10-100x typical) yielding peak efficiencies just above 98%. Advances like the one presented here improve efficiency and density in existing application spaces and open new applications which bulky or inefficient power supplies would otherwise make impractical.

Multiple-Input Single-Output Power Converter for Solar Applications

2.07

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Sponsorship: ARPA-E

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

Efficiency of solar panels grows every year and simultaneously their price drops. Currently, the best efficiencies are achieved by multi-junction solar cells. However, that type of cells has several disadvantages. Cells made of different materials have to be connected in series, parallel or some combination of both to match voltages and currents. Therefore, the efficiency is decreased because cells do not operate at their maximum power points (MPP). Additionally, the materials for multi-junction cells are very expensive and panels cost tens of thousands of dollars per square meter.

The latter problem is currently solved by using concentration optics. One of its advantages is the dramatic decrease of used material. However, it limits the panel working only in direct light and any cloud could reduce the efficiency to zero.

My project is a part of the ARPA-E MOSAIC project for creation of lateral multiple bandgap PV cells, and it proposes further improvements to the existing multi-junction cells. Addition of dispersion to concentration optics allows placing different material cells laterally. Placing a larger silicon cell additionally allows to capture diffused light. Therefore, these proposed solar panels promise high efficiencies of multi-junction panels and low cost of silicon panels. However, since all cells are separated and have different MPPs, it requires multiple-input power electronics to efficiently gather all energy and produce single voltage output.

Different topologies for multiple-input single-output (MISO) power converters were considered, which resulted in selection of MISO buck converter. Since inductors are the components with least energy density, a single-inductor topology was selected. The topology allows efficiently combining 4 power inputs from different solar cells and tracking MPP of each separate input, and therefore, allowing a novel type of solar panels to achieve high power extraction under any illumination conditions and combines advantages of all existing solar panel technologies.

An Energy-Efficient Fully Integrated 1920x1080 H.265/HEVC Decoder with eDRAM

2.08

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Sponsorship: TSMC University Shuttle Program

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Research Interests: Electronics, information processing,multimedia.

Video playback on mobile devices has become extremely popular in recent years to the extent that video accounts for 55% of all mobile data traffic. In response, new video coding standards that efficiently compress video without sacrificing quality have been developed. H.265/HEVC (High Efficiency Video Coding), the state-of-the-art video-coding standard, achieves 2x coding efficiency over its predecessor H.264/AVC (Advanced Video Coding). However, it comes at the cost of increased energy and area for video decoding due to computational complexity and memory accesses. In particular, data movement to/from off-chip DRAM (Dynamic Random-Access Memory) dominates energy consumption, consuming 2.8x-6x more energy per pixel than the processing itself. Accordingly, the focus of this work is to minimize the energy cost of data movement for an H.265/HEVC decoder.

In this work, we propose several techniques to reduce the amount of data movement and optimize for overall system energy. The energy cost of data movement consists of active power for reading from/writing to memory and standby power for retaining memory contents. Through optimized data storage and movement, both active and standby energy cost can be minimized. We demonstrate the proposed techniques in a fully integrated H.265/HEVC decoder that does not require any external components.

Low Power Depth Estimation for Time of Flight Imaging

2.09

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Sponsorship: Analog Devices

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Depth sensing is used in a variety of applications that range from virtual reality to robotics. Time of flight (TOF) cameras, which sense depth by emitting a pulse of light and measuring its return time, are appealing for these applications because they are computationally simple and robust under different ambient lighting conditions. However, the illumination source of TOF cameras requires a significant amount of energy and limits application time for mobile and battery-operated devices. To reduce energy consumption, we propose a hardware-friendly algorithm that leverages RGB images, which can be efficiently collected alongside the TOF camera, to output depth maps without the need of continuously illuminating the scene. The goal is to produce high quality depth sensing while reducing the usage of the TOF camera.

Our approach models the camera image formation process from which the RGB images are obtained and, in particular, how scene motion is reflected in these images. Our algorithm then inverts this model to obtain parameters that describe how the scene has moved, which are then used to update a depth map previously measured by the TOF camera. For new regions that are captured by the RGB image, but not in the previously measured depth map, we also present a technique that exploits spatial similarities in the RGB image to infill its depth. To demonstrate the accuracy of our approach, we present results on both synthetic and real data.

Low Voltage Cold-Start System for Thermal Energy Harvesting using Integrated Magnetics

2.10

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Sponsorship: Texas Instruments

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Research Interests:
Communications, electronic devices, energy harvesting devices & systems, integrated circuit, power management, Si, systems.

Energy harvesting is becoming increasingly popular for enabling long-term sensing and monitoring solutions in remote areas, smart homes, wearable electronics, and industrial applications. Energy harvesting systems need to be able to extract power from the limited energy levels available to them from their surroundings. For this reason, recent boost converters for thermal energy harvesting have been designed to operate from as low as 10mV input voltages. However, they typically need >200mV in order to start up initially, thus wasting potential power that could be harvested from <200mV. Meissner Oscillators are one common solution to this problem as they have been demonstrated to start up from as low as 20mV. However, they require the use of bulky off-chip transformers leading to undesired area overheads. Therefore, a system that is able to start-up from low voltages without using off-chip transformers is desirable.

This research work presents proof-of-concept for a fully integrated start-up system, which can cold-start from <50mV using Texas Instruments' on-chip magnetics and can also be used as an energy harvesting charger for ultra low power applications. The use of lossy on-chip transformers in a Meissner Oscillator, as opposed to high quality off-chip transformers, poses new design and optimization challenges. Hence, we derived intuitive analytical expressions well-suited for use with integrated magnetics to co-optimize the oscillator components. A specially fabricated depletion mode MOS transistor was tested with an off-chip transformer to exhibit oscillations from 3mV DC input voltage. An optimized on-chip transformer, 36x smaller in area than the off-chip transformers, was also fabricated and is pending testing. Furthermore, a switched capacitor DC-DC circuit was designed and tested to boost up the oscillator's output to 1.2V. This complete start-up system for energy harvesting can allow cold start and power extraction from very low voltages without significant area overhead.

Secure Wireless Communications Using Ultra-Fast Bit-Level Frequency Hopping

2.11

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Sponsorship: Texas Instruments

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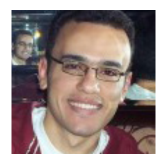
Communications, energy, information processing, power management, systems.

The Internet of Things includes networks of low-power sensors monitoring health, climate, industrial processes, and more. These devices typically communicate wirelessly using the Bluetooth Low Energy protocol, which is vulnerable to selective jamming attacks. With these applications in mind, we propose a novel ultra-low-power transmitter architecture for the 2.4 GHz radio communications band that offers greater security against selective jamming by hopping carrier frequencies within 1 microsecond, allowing each data bit to be transmitted on a separate carrier. The ultra-fast hopping rate prevents jammers from accurately detecting a target transmitter's carrier frequency and initiating interference before the target's next hop. To control the transmitters, we also introduce the Rapid Adaptive Broad-Band frequency-hopping protocol for the Internet of Things (RABBIT). RABBIT is asymmetric, designed for sets of transmitter nodes communicating with a single base station node, and adaptive, dynamically adjusting its configuration based on real-time interference conditions. RABBIT also supports message-driven frequency hopping, which encodes some message information in the choice of channel and thereby permits some information to be communicated even in the presence of interference. RABBIT provides configurable and adaptive security against selective jamming.

uVIO: Energy-Efficient Accelerator for Micro Drone Navigation in GPS-denied Environments

2.12

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



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Drones are getting increasingly popular nowadays, it is reported that their sales have tripled in the last year. Micro drones specifically are easily portable and can fit in your pocket. Equipped with multiple sensors like cameras and inertial measurement unit (IMU), the functionality of drones is getting more powerful and smart (e.g. track objects, build accurate 3D maps and even avoid obstacles). These capabilities are enabled by powerful computing platforms like CPUs and GPUs installed on the drones, which consume a lot of energy. Both the size of these platforms as well as the battery's weight and limited energy make it prohibitive to deploy to micro drones, which can be as small as two inches and operate on very small batteries.

In this project, we present uVIO, an energy-efficient hardware accelerator for micro drone navigation in GPS denied environments. The hardware is co-optimized with the algorithm and the drone design to enable a lightweight drone (~100 grams). The micro drone is equipped with a stereo camera and an IMU and can operate in real time without any external communications. The accelerator is designed to be energy-efficient to operate on a small battery satisfying the overall payload weight of the drone.

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 micro drone as well as the 3D environment via Gauss-Newton algorithm. The implementation is highly parallelized and pipelined to achieve real-time performance and energy efficiency. This accelerator gives a micro 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 indoor exploration and surveillance as well as rescue operations in collapsed buildings.

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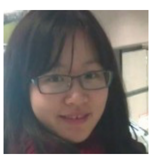
Designing Energy-Efficient Convolutional Neural Networks using Energy-Aware Pruning

2.13

T.-J. Yang, Y.-H. Chen, V. Sze
Sponsorship: DARPA, CICS, Intel, NEC

Deep convolutional neural networks (CNNs) are indispensable to state-of-the-art computer vision algorithms. However, they are still rarely deployed on battery-powered mobile devices, such as smartphones and wearable gadgets, where vision algorithms can enable many revolutionary real-world applications. The key limiting factor is the high energy consumption of CNN processing due to its high computational complexity. While there are many previous efforts that try to reduce the CNN model size or amount of computation, we find that they do not necessarily result in lower energy consumption, and therefore do not serve as a good metric for energy cost estimation.

To close the gap between CNN design and energy consumption optimization, we propose an energy-aware pruning algorithm for CNNs that directly uses energy consumption estimation of a CNN to guide the pruning process. The energy estimation methodology uses parameters extrapolated from actual hardware measurements that target realistic battery-powered system setups. The proposed layer-by-layer pruning algorithm also prunes more aggressively than previously proposed pruning methods by minimizing the error in output feature maps instead of filter weights. For each layer, the weights are first pruned and then locally fine-tuned with a closed-form least-square solution to quickly restore the accuracy. After all layers are pruned, the entire network is further globally fine-tuned using back-propagation. With the proposed pruning method, the energy consumption of AlexNet and GoogLeNet are reduced by 3.7x and 1.6x, respectively, with less than 1% top-5 accuracy loss. Finally, we show that pruning the AlexNet with a reduced number of target classes can greatly decrease the number of weights but the energy reduction is limited.



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Research Interests: Integrated circuits.

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

2.14

X. Yang, H.-S. Lee
Sponsorship: MIT/MTL Gallium Nitride Energy Initiative, Office of Naval Research

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 the 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 ¼ of the conventional 8-bit flash ADC. Therefore, a higher operating speed can be achieved.

We introduced gating logic so that only one interpolator is enabled 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.

Towards Real-Time Super-Resolution on Compressed Video

2.15

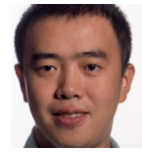
Z. Zhang, V. Sze

High-resolution displays are increasingly popular, calling for faster algorithms to upsample the existing low-resolution video content. State-of-the-art super-resolution algorithms mainly address the visual quality of the output instead of real-time throughput. Even the fastest existing super-resolution algorithm, Super-Resolution Convolutional Neural Network (SRCNN), takes 0.4 second to process a single frame of size 256x256. This is far behind the requirement of a real-time super-resolution system, which should be capable of processing 30 frames per second on full HD videos (1920x1080).

We propose a framework called Free Adaptive Super-Resolution via Transfer (FAST) to accelerate any image based super-resolution algorithm running on compressed videos. FAST leverages the similarity between adjacent frames in a video. Given the output of a super-resolution algorithm on one frame, FAST adaptively transfers the super-resolution to the adjacent frame so that we can avoid running the super-resolution algorithm on the adjacent frame. The transferring process has negligible computation cost because the required information including motion vectors, block size, and prediction residual are already embedded in the compressed video for free.

FAST also adapts to video content, which is composed of frames with varying block sizes. It adaptively enables and disables transfer for each block depending on the quality of motion compensation of the video encoder. Note that the blocks are non-overlapping to avoid redundant computations. The resulting artifacts are handled by low complexity deblocking filters.

We evaluate FAST with existing state-of-the-art super-resolution algorithms on the common test sequences that were used in the development of the HEVC video compression standard. FAST accelerates all the tested super-resolution algorithms by up to an order of magnitude with acceptable quality loss of up to 0.2 dB. This proves that FAST can accelerate any super-resolution algorithm, potentially enable running super-resolution algorithms to upsample streamed videos for large screens in real time.



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Transceiver Design of THz Dielectric-Waveguide-Based Inter-Chip Communication System

2.16

Z. Hu, J. Holloway, R. Han

Sponsorship: Office of Naval Research

Rapid development of data centers and high-performance computation platforms are calling for high data-rate, high density and energy efficient data links, and researchers have put much effort on links based on copper wirelines and optical fibers. However, the former class has the problem of limited bandwidth (normally <60GHz) while the latter has the problem of compatibility with standard IC processes and high cost. Our research instead explores data transmission in the THz band using dielectric waveguide, which can potentially outperform other solutions with large bandwidth, full integration with available technologies, and low power consumption. This project aims at a link with a data rate of 100Gbps and an energy efficiency of <1pJ/bit.

The system includes a) polymer waveguide and waveguide-to-chip interface, which have already been fabricated and measured in our group, exhibiting ~100GHz bandwidth and b) a high-speed transceiver in silicon. To take full advantage of the broad bandwidth and to lower the overhead of high-speed digital processing, a wavelength-division multiplexing scheme is adopted. Within each channel, at the transmitter side, a modulator is implemented to directly turn on/off a free-running oscillator, and at the receiver side, a passive homodyne detector is used to sense the on-off keying signal. The scheme requires no phase-locked loops, nor phase modulator on both sides, and thus consumes much less power.

Implemented in a 130-nm Silicon-Germanium Bipolar/CMOS process, our THz dielectric-waveguide-based link is expected to demonstrate potential for future data-intensive applications.

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Thermal Energy Harvesting for Self-Powered Smart Home Sensors

2.17

M. Yun, E. Ustun, P. Nadeau, P. Nadeau, A. P. Chandrakasan

Sponsorship: Hong Kong Innovation and Technology Fund (ITS/195/14FP)

We investigate the use of thermoelectric energy harvesting for embedded, self-powered sensor nodes in smart homes. In particular, one such application is self-powered pressure sensing in vacuum insulation panels for buildings. Vacuum insulation panels boast vast improvements in thermal efficiency, but they can potentially develop leaks that compromise the insulation. The thermal difference developed across the panels could be applied across a thermoelectric generator to power a wireless sensor that monitors and reports pressure level.

To create a proof-of-concept, we first modelled the available power using the difference between room temperature and outside temperature using historical weather data. Then, we measured the thermoelectric generator's actual power output by combining the generator with a vacuum insulation panel and mounting the assembly inside a window for experiments.

Finally, we determined the feasibility of using the established thermal gradient to power a sensor node. We show that thermoelectric energy harvesting could enable a new class of embedded, maintenance-free, self-powered sensors for smart homes.

Engineering Phonons and their Interactions in PbS Nanocrystals

3.01

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Research Interests: Electronic devices, electronics, energy, energy harvesting devices & systems, lasers, light-emitting diodes, nanomanufacturing, nanomaterials, nanotechnology, optoelectronics, organic materials, photonics, photovoltaics.

New nanostructured semiconductor materials, manufactured by chemical methods, are a broad class of materials that are of ever-growing interest for energy device applications. Although the efficiencies of LEDs and solar cells based on such materials have been successfully improved, energy efficiencies must still increase for commercial application.

Fundamentally, all forms of energy loss do ultimately transform available free energy into heat, i.e., phonons carrying the vibrational energy. In semiconductors, this happens through charge carrier processes, such as non-radiative recombination, trapping, and transport of charge carriers. In nanostructured semiconductors, we have recently shown that this coupling between electrons and phonons is generally strong due to the soft surfaces of the materials, which can lead to large non-radiative transition rates of electrons.

Here, we show that the phonon spectrum in nanostructured semiconductors can be systematically modified and can be used to modify the opto-electronic properties of the material. Using recent advantages in the understanding of the surface chemistry of PbS nanocrystals, we are able to gradually remove surface ligands without replacement to destabilize the nanocrystal surface and increase the strength of phonon interactions.

We quantify the changes to the phonon properties of the material directly by light absorption at THz frequencies and by determining the atomic mean square displacement through x-ray diffraction. We further probe the changes to the phonon properties indirectly by its influence on the optical properties of the semiconductor, i.e. the near infrared absorption and emission spectra and the luminescence lifetime.

In particular, we discuss how the engineering of the PDOS can be used to reduce energy loss processes.

Efficient Spatial Variation Characterization via Matrix Completion

3.02

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

Semiconductor manufacturing is subject to spatial and temporal variations. In order to predict and reduce the impact of variations in fabrication, various silicon integrated circuit analysis and optimization approaches have been proposed. To accurately model circuit performance and yield, these methods rely on testing data from fabricated devices and circuits. However, integrated circuit testing is not free. Large numbers of test structures must be carefully designed, fabricated, and measured and thus the cost is considerable. To reduce the cost of measurement, instead of measuring large numbers of "expensive" variables, mathematical or statistical models are constructed to predict some or all of these variables.

In this project, we seek to exploit recent developments in another important area, compressed sensing, to build a virtual metrology system for the spatial variation, the variations among devices at different positions of the same die or wafer. This new technique is based on recent developments in matrix completion, enabling estimation of spatial variations across wafers or dies with a small number of randomly picked sampling points while still achieving fairly high accuracy. This approach can be easily generalized, including for estimation of mixed spatial and structure or device type information.

Force-Modulated Growth of Carbon Nanotubes

3.03

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Sponsorship: National Science Foundation, Department of Energy

Carbon nanotubes (CNTs) can be synthesized in vertically aligned arrays, or "CNT forests," using chemical vapor deposition (CVD). However, the CVD process results in a non-uniform population of CNTs that ultimately causes a degradation of the forest properties so that the potential of CNTs cannot be fully realized. During the growth, CNTs mechanically interact with each other, inducing forces that have been suggested to contribute to the difficulty in controlling the development of the forest population. We investigate the effect of mechanical forces by applying external forces during the CVD process using a custom-built CVD reaction chamber. Using a combination of in-situ height and force measurements with ex-situ electron microscopy and small angle X-ray scattering characterization techniques, we demonstrate that the applied forces significantly alter the growth rate, morphology, and density of the CNTs within the forest, thus confirming that mechanical forces can strongly influence and even control the evolution of the CNT's population.

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Self-assembling Pattern of Thin-film Magneto-impedance Structures for Bio Applications

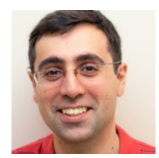
3.04

E. Fernandez, L. Cheng, A. García-Arribas, A. V. Svalov, C. A. Ross

The Giant Magneto-impedance (GMI) effect is the change of the total impedance of ferro-magnetic conductor (Z) under application of external magnetic field (H) for a high frequency electric current. Because of the large GMI sensitivity with a field range from 0.1 mT to 1 nT, numerous attempts have been made to develop sensing devices based on GMI. GMI sensor competes with Giant Magneto-Resistance, fluxgate, and Anisotropic Magneto-Resistance sensors. In this work, we use an optimum combination of magnetic and non-magnetic layers that maximizes the GMI performance.

In this work, we focus our study on applications for detecting magnetic iron oxide nanoparticles. For fabrication simplicity, we used an open flux configuration stack of [Py(100 nm)/Ti(6 nm)]4 /Cu(400 nm)/ [Ti(6 nm)/Py(100 nm)]4. Two set of 10 mm long and 0.5 mm wide samples were prepared by dc sputtering. In one of them, we used a self-assembly block copolymer (PS-PDMS) to pattern a series of periodic lines, 46 nm wide and 50 nm deep with a pitch of 80 nm into the top permalloy layer. The top permalloy layer is patterned to break the magnetic flux. Once a magnetic particle settles on one of these nano-patterned trenches, the magnetic flux is closed and produces an increase on the impedance. The other sample is a reference to test the GMI detection of magnetic particles.

We measured the samples in a frequency range from 300 kHz up to 300 MHz, at fields up to 150 Oe. The magneto-impedance ratio of the sample without trenches, calculated from the absolute value of the impedance Z, was MI = 100*(Z-Zmin)/Zmin = 200 % and the sensitivity, calculated as the field derivative of the MI ratio, was 55 %/Oe.



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GaAsP/InGaP Heterojunction Bipolar Transistors for III-V/Si Microelectronics Integration

3.05

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Sponsorship: Center for Energy Efficient Electronics Science (E3S)

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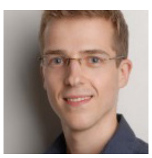
Research Interests: 2D materials, electronic devices, electronics, energy, III-Vs, integrated circuits, lasers, light-emitting diodes, MEMS & NEMS, nanomanufacturing, nanomaterials, nanotechnology, optoelectronics, photonics, photovoltaics, Si, SiGe and Ge, semiconductor epitaxy, thin-film characterization.

Device-quality III-V semiconductors grown epitaxially on silicon substrates have the potential to address the need for higher bandgap materials for analog I/O circuitry in applications such as mobile devices. This monolithically-integrated approach reduces production costs and takes advantage of silicon as a well-demonstrated platform for digital CMOS circuitry. In this work, we explore the use of $GaAs_xP_{1-x}/In_yGa_{1-y}P$ heterostructures grown on silicon substrates for the fabrication of heterojunction bipolar transistors (HBTs). $GaAs_xP_{1-x}$-based transistors (with x=0.7-0.9) have the potential to operate at higher voltages than more common GaAs-based devices because of their higher band gaps. They also have lattice constants that are closer to silicon, facilitating easier monolithic integration.

$GaAs_xP_{1-x}/In_yGa_{1-y}P$ heterostructures were grown by metalorganic chemical vapor deposition on both GaAs and silicon substrates, with x varying from 0.8 to 1 and y varying to keep the device layers lattice matched. Lattice mismatch between the device layers and the substrate is accommodated by $GaAs_xP_{1-x}$ and Si_zGe_{1-z} compositionally graded buffers, respectively. Threading dislocation densities less than 10^7 cm^{-2} were achieved. HBTs were fabricated with an (N) InGaP emitter, a (p+) GaAsP base, and an (n-) GaAsP collector. Heavy p-type C doping of GaAsP was studied for the growth of the base layers. DC current gain and breakdown voltage were measured as a function of composition.

We have found that for the HBTs grown on GaAs substrates, current gain does not depend largely on composition, but on other factors such as sidewall passivation and current density. In addition, the GaAsP/InGaP band alignment was extracted from the HBT IV data. HBTs grown on Si substrates show much lower current gain than those grown on GaAs substrates. This is attributed to misfit dislocations that form along the emitter-base interface.



Building Synthetic Cells for Sensing Applications

3.06

M. Hempel, J. Kong, T. Palacios

Sponsorship: Air Force Office of Scientific Research

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

Miniaturized sensors equipped with communication capabilities enable a new paradigm of sensing in areas such as health care or environmental monitoring. For example, instead of measuring your blood sugar by pricking your finger and analyzing a drop of blood externally, a microscopic sensor platform in the blood stream could sense the glucose concentration internally and communicate data to the outside world non-invasively.

In this project, we work towards this vision by developing a microscopic sensor platform, called synthetic cell or SynCell that can sense chemical substances in liquid media. Upon exposure to a specific substance, the chemical sensors onboard the SynCell are designed to permanently change their electrical resistance. Later on, they will be retrieved by using magnetic pads and analyzed externally.

To realize this concept, we designed a 100 µm wide flexible polymer disk that has three chemical sensors, a stored ID number in the form of ROM transistors as well as integrated magnetic readout pads. The transistor channels and sensors are made of a single atomic layer of molybdenum disulfide which is a perfect material for this application because it is flexible and easy to integrate into membrane-like electronics. Furthermore, it is an excellent material to build digital electronics and very sensitive sensors.

With our first iteration of the SynCells, we demonstrated functional transistors and developed a process to lift the disks off from the fabrication substrate and disperse them in solution. We also showed the ability to manipulate the SynCells by external magnetic fields. In the next steps we want show fully functional SynCells and demonstrate the ability to magnetically retrieve them.

Experiments and Numerical Analysis on Air Bearing Slumping of Segmented Thin-shell Mirrors for X-ray Telescopes

3.07

H. Zuo, M. Schattenburg

Sponsorship: NASA APRA, MIT Kavli Institute Research Investment Fund

Air bearing slumping of thin glass sheets onto high precision mandrels was used by NASA Goddard Space Flight Center to fabricate the NuSTAR telescope with spectacular success. Though this process generates mirrors with good resolution, it requires long thermal cycles and produces mid-range spatial frequency errors due to the anti-stick mandrel coatings.

Over the last few years, MIT Space Nanotechnology Lab has developed a new slumping process which utilizes a pair of porous air bearing mandrels through which compressed nitrogen is forced, with the round flat glass sheet floating on a thin layer of nitrogen during the thermal cycle. This results in glass with reduced mid-range spatial frequency errors and can be accomplished in much shorter thermal cycles. Recent design and tests have been focused on improvements to a horizontal slumping of mirrors, which requires active control with fiber sensing techniques to measure the glass location and Inconel bellows to control the apparatus tilt using compressed nitrogen.

During the past year, we improved the control loop to reduce the response time from 10 minutes to 20 seconds through a series of system identification tests. We conducted many experiments with this improved slumping system and designed a user interface to incorporate the Shack-Hartmann raw images to reconstruct wafer surfaces. We examined the influence of the nitrogen pressure, the thickness of air gaps and the design of thermal cycles to the final shape of the wafers. To complement the experiments and to better understand the underlying mechanism, we utilized ADINA to carry out finite element analysis of the deformation of glass during the heating processes. We proved that for the 2D axisymmetric circular wafer, experimental approaches and numerical simulations have comparable results. We also discovered the crucial impacts of bearing permeability to the resulting shape of the wafers.

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Research Interests:
Nanomanufacturing, optoelectronics.

Low-Frequency Interlayer Raman Modes to Probe Interfacial Stacking and Coupling in Twisted Bilayer MoS_2

3.08

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Sponsorship: U.S. Department of Energy, Oak Ridge National Laboratory

Van der Waals homo- and hetero- structures assembled by stamping monolayers together present optoelectronic properties suitable for diverse applications. Understanding the details of the interlayer stacking and resulting coupling is crucial for tuning these properties. We investigated the low-frequency interlayer shear and breathing Raman modes (<50 cm^{-1}) in twisted bilayer MoS_2 by Raman spectroscopy and first-principles modeling. Twisting significantly alters the interlayer stacking and coupling, leading to notable frequency and intensity changes of low-frequency modes. The frequency variation can be up to 8 cm^{-1} and the intensity can vary by a factor of ~5 for twisting angles near 0° and 60°, where the stacking is a mixture of high-symmetry stacking patterns and is thus sensitive to twisting. For twisting angles between 20° and 40°, the interlayer coupling is nearly constant since the stacking results in mismatched lattices over the entire sample. It follows that the Raman signature is relatively uniform. Note that for some samples, multiple breathing mode peaks appear, indicating non-uniform coupling across the interface. In contrast to the low-frequency interlayer modes, high-frequency intralayer Raman modes are much less sensitive to interlayer stacking and coupling. This research demonstrates the effectiveness of low-frequency Raman modes for probing the interfacial coupling and environment of twisted bilayer MoS_2, and potentially other two-dimensional materials and heterostructures.

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Chemical Vapor Deposition of Multiple Transition Metal Disulfides in One Synthesis Step

3.09

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Sponsorship: Air Force Office of Scientific Research FATE MURI, DOE, MIT-SUTD Postdoctoral Fellows Program

Recently, semiconducting 2D materials, such as transition metal dichalcogenides (TMDs including MoS_2, WS_2, WSe_2 etc.) and phosphorene, have attracted tremendous attention owing to their extraordinary properties, setting the stage for new breakthroughs in fundamental materials science and a variety of applications, from electronics to biochemical sensing. Various techniques have been explored to obtain monolayer TMDs. To date, chemical vapor deposition (CVD) synthesis using transition metal oxide and chalcogenide solid precursors is the most commonly adapted approach. Notably, the amount of precursors used is normally superfluous, giving rise to the reactions between precursors in each of their crucibles. Hence, one CVD setup is usually dedicated to the synthesis of only one type of TMDs to avoid cross-contamination. In addition, it is impossible to obtain different types of TMDs in one synthesis step.

Here, we report a new technique to synthesize multiple TMDs on separate substrates in one CVD process, effectively reducing the thermal budget required. By pruning the amount of precursors used and placing all growth substrates in slanting position, instead of the conventional horizontal position, we have been able to simultaneously grow different types of TMD on separate substrates using the same growth chamber. Through computational fluid dynamics modelling, we found that gas species trapped within those slanting substrates in our CVD setup are unable to escape from the trap, and thus avoiding the cross-contamination issue. The synthesized TMD films exhibit respectable properties as confirmed by Raman, PL, XPS, STEM analyses, and electrical measurements. In short, the idea of "one-pot" synthesis demonstrated in this work provides a cost-effective solution for mass production of multiple TMD films at the same time, and importantly, the proposed CVD technique is compatible with the state-of-the-art CMOS fabrication technology.

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2D Material Sensing Systems

3.10

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Sponsorship: Air Force Office of Scientific Research FATE MURI

The overarching goal of this project is to develop a 2D material-based sensing system that is self-powered and can collect specific data about its environment. To accomplish such a goal, this project will focus on studying the material characteristics of chemical vapor deposition (CVD) grown 2D materials and from this point develop devices that can harvest energy from their environment and power a semiconducting sensing component. It will develop electronics based on graphene, molybdenum disulfide (MoS_2), and tungsten diselenide (WSe_2). This work will utilize CVD grown materials to demonstrate the system's scalability. The current sub-focus of this project explores the use of CVD MoS_2 to fabricate chemical sensors.

The progress detailed here develops a process flow for creating pH sensors and characterizing their sensitivity, stability, and response time. It will also consider variation of device performance across a high quality monolayer MoS_2 sample, as well as possible changes in photoluminescence due to varying pH solutions. The analysis from this portion of the project will lay the foundation for developing more complex sensing architectures that can be optimized to detect specific chemicals of interest.

Integrated Photonics and Nanofluidic Devices on CMOS

3.11

H. Meng, R. Ram

Sponsorship: DARPA

Planar CMOS process could be used to integrate photonic and nanofluidic devices monolithically. By bringing optical detectors to the near field of the nanofluidic channel, better collection efficiency and resolution than far-field imaging system is possible. The scalability and precision of CMOS process enable applications that require high throughput, such as genome mapping and sequencing.

Previous work in our group demonstrated integrated optoelectronic devices in commercial CMOS platform, including optical waveguides, ring resonators, modulators, and detectors. We propose an opto-nanofluidic architecture and integrated near-field detection system, leveraging the existing optical devices. By placing silicon-based APDs within near-field of the nanofluidic channel, light source in the channel emits preferentially into the high index silicon. As a result, better collection efficiency and resolution of visible wavelength can be obtained. A method of fabricating nanofluidic channels using polysilicon sacrificial layer is presented. Sub-100nm nanofluidic channels with aspect ratio more than 100:1 are demonstrated. Additionally, loading aqueous liquid into the nano-channels is presented.

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Biological devices & systems, microfluidic devices & systems, optoelectronics, photonics, Si.

Scaling and Carrier Transport Properties of Monolayer MoS_2 Transistors

3.12

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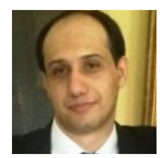
Sponsorship: Office of Naval Research, Army Research Office

2D crystals of layered transition metal dichalcogenides such as Molybdenum disulfide (MoS_2) are ideal candidates for aggressive miniaturization of field-effect transistors (FETs) to the single digit nanometer scale. In addition to large bandgap, chemical stability, and compatibility with CMOS processes, this class of materials can benefit from their atomically thin body with dangling-bond-free surfaces. Because of this and their ultra-small body thickness, transistor subthreshold swing and drain-induced barrier lowering (DIBL) coefficient in such films can be significantly smaller than for conventional thin-body semiconductors. In particular, monolayer-MoS_2 (ML-MoS_2), because of its bandgap of 1.8 eV yields high I_{on}/I_{off} ratio FETs, while its low dielectric constant, ε_ρ = 4-7, and atomically thin body, t = 0.7 nm, facilitate the reduction of characteristic scaling length.

We previously reported a 15-nm channel length MoS_2 FET using monolayer graphene as the Source/Drain contacts. In this work, by exploiting the semiconducting to metallic phase transition in MoS_2, we demonstrate a 7.5 nm transistor channel length by patterning of ML-MoS_2 in a periodic chain of homojunction semiconducting-(2H) and metallic-phase (1T') MoS_2 regions. Sub-10 nm 1T'/2H MoS_2 patterning is achieved by directed self-assembly (DSA) of block copolymers (BCP: PDMS/polystyrene) technique. The transistor chain shows I_{on}/I_{off} greater than 10^6 with I_{off} ~100 pA/µm. Modeling of the resulting characteristics reveals that the 2H/1T' MoS_2 homojunction has a resistance of 75 Ω.µm while the 2H-MoS_2 exhibits low-field mobility of ~20 cm^2/V.s and carrier injection velocity of ~10^6 cm/s.



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Research Interests: 2D materials, biological devices & systems, bioMEMS, electronic devices, electronics, energy, energy harvesting devices & systems, field-fmitter devices, GaN, III-Vs, integrated circuits, light-emitting diodes, MEMS & NEMS, nanomanufacturing, nanomaterials, nanotechnology, optoelectronics, photonics, photovoltaics, Quantum devices, sensors, Si, SiGe and Ge, spintronics, transducers.

CMP and Wafer Bonding of GaAsP on Silicon

3.13

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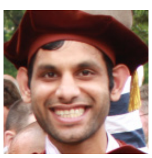
Compositionally graded, strain relaxed buffers have been used to produce semiconductor alloys that have a large lattice mismatch with respect to the substrate. The entire $Si_{1-x}Ge_x$ (on Si) and $In_xGa_{1-x}As$ (on GaAs), composition space can be obtained with dislocation density lower than $10^6 cm^{-2}$. These graded buffers tend to be several microns thick and have a characteristic "crosshatch" surface morphology with peak- valley features up to 100nm high.

Chemical-Mechanical polishing (CMP) can be used to smooth these surfaces to sub nm rms roughness. CMP of these epitaxial layers require the polishing to be accomplished without removal of several microns of material, in contrast to CMP of bulk wafers. CMP of SiGe alloy films have already been developed for a wide range of Ge composition but limited work has been done for III-V alloys. This work focuses on developing CMP of a $GaAs_{75}P_{25}/Si_{1-x}Ge_x/Si$ alloy using NaOCl and citric acid based solutions. The surface topography is characterized using profilometry and AFM to understand the effect of pH, concentration of the oxidizing agent and applied pressure during the CMP.

The planar surface post CMP is not only more favorable for any device processing on these alloys but also is required for wafer bonding. Layer transfer of device layers employing direct wafer bonding and reusing the virtual substrate of the strain relaxed alloy can decrease the cost of using a thick strain relaxed compositionally graded buffer. Thermocompression bonding is used to bond the polished $GaAs_{75}P_{25}/Si_{1-x}Ge_x/Si$ alloy to another Si substrate. The interface conductance is measured to enable a tandem dual junction PV system with a $GaAs_{75}P_{25}$ (1.7 eV) top cell and a Si bottom cell.



Synthesis and Characterization of Two-Dimensional Material Alloys

3.14

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

Two-dimensional transition metal dichalcogenide (2D-TMD) semiconductors have unique optical (enhanced light emission compared to bulk), electrical (high on-off ratios) and structural (stable and flexible free-standing atomic layers) properties. The possibilities for applications can be dramatically expanded by synthesizing alloyed materials and hetero-structures. However, growth conditions for synthesis of these alloyed materials are not well understood.

Here we present our recent work on the synthesis and characterization of alloyed materials for greater functionality. We discuss optimized growth conditions for alloyed materials and phase segregation (inter-mixing of alloy components) depending on growth temperatures. The 2D-alloyed materials are grown using a three-zone chemical vapor deposition (CVD) system, offering precise control on the temperature and delivery of precursors as well as growth kinetics. The synthesis method is very flexible for choice of precursors, with molybdenum disulfide and tungsten disulfide chosen as exemplary materials for this study. The as-grown materials are characterized for structural homogeneity, strain, and defects through a combination of optical and electron microscopy techniques. Optical microscopy, micro-Raman scattering, and micro-photoluminescence measurements are used to quantify homogeneity, defects, and phase-segregation on the millimeter to micron scale. Further, a high resolution transmission electron microscope (HRTEM) is used to characterize defects (vacancies, line defects) and atomic ordering in the alloys and hetero-structures, on the micrometer to sub-nanometer scale.

These complementary characterization techniques are useful for analyzing and optimizing different growth regimes, and critical for extending CVD as a scalable synthesis method for functional alloys. These alloys can be used in photovoltaics, as heat blockers and thermoelectric materials, as well as tunable electronic materials.

Improving VLSI System Energy-Efficiency by Optimizing Nanotechnology Design and Fabrication: Case Study with CNFETs

3.15

T. Srimani, S. Kim, G. Hills, M. Shulaker

Emerging nanotechnologies promise major energy efficiency benefits; for instance, carbon nanotube field-effect transistors (CNFETs) are projected to improve the energy-delay product (EDP) of digital very-large-scale integrated (VLSI) circuits by an order-of-magnitude vs. silicon CMOS. However, these projected benefits are restricted to improvements resulting from an alternative channel material.

Here we demonstrate that by co-optimizing the fabrication, device structure, and design of CNFETs for VLSI digital circuits, EDP can improve by an additional factor of 2.0× over previous projections (resulting in a ~20× EDP improvement over silicon CMOS), while simultaneously relaxing requirements on controlling CNT process variations. Furthermore, this work is both applicable to a broad range of emerging 1D and 2D nanomaterials and guides future research directions on emerging nanotechnologies for high-performance digital logic VLSI. Specifically, we show: 1) While significant research focuses on realizing top-gate and advanced gate-all-around CNFETs, a new local bottom-gate (LBG) device structure – which is naturally enabled by emerging nanotechnologies - significantly reduces device-level parasitics by >2.5× compared to conventional top-gate FET structures, resulting in >1.4× EDP benefit for VLSI digital circuits.; 2) While significant research focuses on realizing well-controlled sub-lithographic inter-CNT spacing of precisely 4-5 nm, analyzing VLSI scale CNFET circuits (e.g., considering effects in realistic circuits such as wire parasitics) demonstrates that re-optimizing device-level parameters for bottom-gate CNFETs, with CNTs deposited immediately adjacent to one another to form a "monolayer", both improves EDP and relaxes processing requirements by not demanding exact and accurate placement of CNTs at sub-lithographic pitches.; 3) Our re-optimized design point is simultaneously robust to variations: today's variations would result in <5% speed degradation with no energy cost. In contrast, previous design points without optimizing device structure and subsequent device-level parameters would suffer >20% speed degradation given today's processing parameters, requiring significantly improved processing co-optimized with design to overcome CNT variations.

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Direct-write Assembly of Colloidal Materials

3.16

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Sponsorship: National Science Foundation

Evaporative self-assembly can be used to assemble colloidal building block particles with varying degrees of order and scale. These particles, when assembled into a solid, can attain emergent properties, such as an electronic or photonic band gap. However, to date, self-assembly of colloidal materials is limited to planar films on substrates. Extending colloidal self-assembly to three dimensions would enable new applications uniquely enabled by macroscale colloidal crystals.

Here, we demonstrate a direct-write technique capable of assembling colloidal particles into millimeter-scale freestanding structures. Using a custom-built liquid dispense apparatus, we precisely extrude an aqueous polystyrene particle suspension from a fine needle onto a temperature controlled substrate. By balancing the rate of dispense with the rate of water evaporation, the polystyrene particles are continuously assembled into a crystalline solid. We propose that direct-write assembly has the potential to be adapted to a vast library of building blocks for building functional materials such as photonic crystals, quantum dot solids, and metamaterials.

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Graphene-on-GaN Hot Electron Transistor

3.17

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Sponsorship: Army Research Office

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

Hot electron transistors (HET) are promising devices that may enable ultra-high frequency operation. In an HET, carrier transport is due to injection of hot electrons from an emitter to a collector, which is modulated by a base electrode. Therefore, ultra-thin base electrodes are needed to facilitate ultra-short transit time and high performance for the THz operation range. In this regard, graphene, the thinnest conductive membrane in nature, is considered the best candidate for the base material in HETs.

The existing graphene-base HETs with SiO_2/Si as emitter stack suffer from both low current gain and low output current density. We previously demonstrated a vertical graphene-on-GaN HET with a record high current density and current saturation. Nevertheless, the device showed a relatively high turn-on voltage due to a thick barrier. In this work, we systematically study the effect of the tunnel barrier width on the on-current and turn-on voltage of the heterojunction. The current-voltage characteristics show that the turn-on voltage decreases significantly with barrier thickness. The measured current density (~10 A/cm^2 at 2V) in the modified graphene-GaN diode is comparable to the values reported in the literature for all-GaN HETs. The C-V measurements show a clear transition from depletion to accumulation for a typical GaN-based capacitor. The valleys in the accumulation region correspond to the graphene quantum capacitance, which is in series with the barrier capacitance. The presence of this feature indicates strong Fermi-level modulation in graphene near its Dirac point. Finally, we fabricate HETs with optimized geometry. The transport study of the optimized device shows high output current density (50 A/cm^2), current gain (3) and ballistic injection efficiency of 75%, all record values among the graphene-base HETs.

Microfluidics and Computational Imaging for Measuring Cells' Intrinsic Properties

4.01

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Sponsorship: Bose Research Award

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Scientific-grade optical microscopes have been the powerful tools for microfluidics as they can be used to observe the behavior of micro-objects of interest inside microfluidic devices. While conventional optical microscopes are limited by the small field of view (FOV), e.g. ~1-2 square millimeters for a 10X objective, the footprint of a microfluidic device is often on the scale of square centimeters. This mismatch between the microscopy FOV and the device footprint restricts the number of micro-objects that can be simultaneously viewed and tracked.

Computational microscopy is one approach to providing a larger FOV without sacrificing resolution. We have been combining visual observation from large FOV computational microscopy with separation of cells via a label-free microfluidic platform in order to study intrinsic properties of cells, such as cell size. This system allows for parallel tracking of multiple cells in a large FOV. We show characterization of the platform along with a set of prototypical microfluidic cell separation devices.

Modelling and Controlling Variations in Advanced 2.5D Packaging Fabrication

4.02

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Sponsorship: Taiwan Semiconductor Manufacturing Company

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Molecular & polymeric materials, nanomanufacturing, spin coating, modeling.

Re-distribution layers (RDLs) are separate packaging layers dedicated to connecting dies with each other and to external I/O ports in advanced 2.5D packaging technologies. These layers can be made smaller than the bulky metal traces in conventional substrate packaging, reducing electrical delay and power consumption. Currently, the damascene process is the most common method to create the copper traces in RDLs. However, due to the required inclusion of chemical mechanical polishing (CMP), this process is significantly more expensive than semi-additive electrochemical plating (ECP) and dielectric spin-coating (DSC) processes. The semi-additive techniques are typically avoided as, without CMP, they suffer from thickness variations following the fabrication of each layer. As multiple layers are fabricated, these variations compound and can result in a structure with significant topographical and electrical performance concerns.

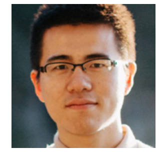
In this study, we model and predict the non-uniformities due to both processes and propose dummy fill and cheesing patterns which control the variations of each process. We first design test vehicles (TVs) which represent topographies common in RDLs, most notably the copper lines and vias, and use these to experimentally determine the thickness variations caused by each process. We then develop empirical models based on these results. The DSC process is modeled as a convolution between the underlying topography (typically the copper lines) and an appropriately chosen impulse response, while the ECP process is modeled as a convolution between the copper layout and a second impulse response. Finally, we present dummy fill and cheesing patterns have the potential to control the variations of both processes for any arbitrary layout.

Evaporation from Ultra-Thin Nanoporous Membrane into Air

4.03

Z. Lu, K. L. Wilke, E. N. Wang

Sponsorship: Air Force Office of Scientific Research



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Available from December 2017.

Research Interests: Thermal structures, devices & systems.

Evaporation from micro/nanostructures plays an important role in nature (e.g., transpiration and perspiration) and shows great promise for water desalination and thermal management of electronics. We experimentally investigated evaporation from a microfabricated, free-standing, metal-coated, ultrathin (~ 300 nm in thickness), nanoporous (~ 100 nm in pore diameter) membrane. We defined the nanopores with interference lithography and reactive ion etch in a silicon nitride membrane layer. The membrane was then suspended using KOH back etch. Finally, we deposited the metal layer with e-beam evaporation and shadow masking.

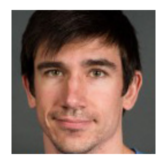
Our structure achieves small viscous loss and large capillary pressure simultaneously, which facilitates interfacial transport. During the experiment, liquid wicks into the metal-coated membrane which is resistively heated to induce evaporation into the air ambient. The heater is also used as a resistive temperature detector to monitor the liquid-vapor interface temperature. We measured the interfacial thermal resistance and demonstrated that the heat flux averaged over the interface area can be as high as ~ 700 W/cm^2 with pure evaporation. This study helps obtain a fundamental understanding of interfacial heat/mass transfer and paves way for high flux applications of phase change devices.

Electrowetting-on-Dielectric Actuation of a Translational and Angular Manipulation Stage

4.04

D. J. Preston, A. Anders, B. Barabadi, E. Tio, Y. Zhu, D. A. Dai, E. N. Wang

Sponsorship: Office of Naval Research, National Science Foundation



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Adhesion and friction during physical contact of solid components in microelectromechanical systems (MEMS) often lead to device failure. Translational stages that are fabricated with traditional silicon MEMS typically face these tribological concerns. This work addresses these concerns by developing a MEMS vertical translation, or focusing, stage that uses electrowetting-on-dielectric (EWOD) as the actuating mechanism. EWOD has the potential to eliminate solid-solid contact by actuating through deformation of liquid droplets placed between the stage and base to achieve stage displacement. Our EWOD stage is capable of linear spatial manipulation with resolution of 10 µm over a maximum range of 130 µm and angular deflection of approximately ±1°, comparable to piezoelectric actuators. We also developed a model that suggests a higher intrinsic contact angle on the EWOD surface can further improve the translational range, which was validated experimentally by comparing different surface coatings. The capability to operate the stage without solid-solid contact offers potential improvements for applications in micro-optics, actuators, and other MEMS devices.

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Research Interests: 2D materials, electronic devices, electronics, energy harvesting devices & systems, GaN, III-Vs, integrated circuits, MEMS & NEMS, power management

MEMS-based Energy Harvesting System for Machine Health Monitoring

4.05

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Sponsorship: Analog Devices Inc.

Vibration-based machine health monitoring provides an efficient method of tracking real-time performance of machines to enable predictive maintenance and avoid machine down-time. Sensors are attached to the vibrating parts that can transmit data indicative of machine health. The key challenges of designing such systems are: building sensors that can operate at low vibration signals, tolerance to manufacturing variations, small form-factor, designing low-power electronics for battery-less operation, and efficient power extraction.

A Lorentz force based MEMS energy harvesting system is proposed that can extract 50 μW from machine vibrations around 50 Hz with external acceleration in the range of 0.2-1 g. The harvester consists of a spring-mass system fabricated using standard Si-MEMS process that oscillates under external vibrations. Magnets embedded in the mass create time varying magnetic flux during their translational motion. Voltage is induced in the windings placed above and below the plane of motion of the spring-mass system in accordance with Lenz's law. The harvester is designed to have a matched translational resonance frequency of 50 Hz to maximize power extraction, with higher alternate resonant modes. The geometry parameters are optimized to achieve a power output of 100 μW, while retaining compactness and mechanical stability. The associated power electronics is 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 to perform impedance tuning and reactive power conditioning for maximizing power extraction under 5% variation in harvester-resonant frequency due to manufacturing tolerances. The circuit also achieves cold-start up using Meissner-oscillator topology that can start from low voltages of ~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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Microfabrication-Based Technologies for Large-Scale Recording of Neural Activity in the Brain

4.06

J. Scholvin, C. G. Fonstad, E. S. Boyden
Sponsorship: NIH, NYSCF, CBMM, Simons Center for the Social Brain

A major goal of neuroscience is to understand how the activity of individual neurons yields network dynamics, and how network dynamics yields behavior (and causes disease states). To reach this goal, innovative neuro-technologies with orders-of-magnitude improvements over traditional methods are required. Nanofabrication can provide the scalable technology platform necessary to record with single-spike resolution the electrical activity from a large number of individual neurons, in parallel and across different regions of the brain. By combining innovations in fabrication, design, and system integration, we can scale the number of neural recording sites: from traditionally a small number of sparse sites, to currently over 1000 high-density sites, and in the future beyond hundreds of thousands of sites distributed through many brain regions.

In this work, we will introduce the technological building blocks and their performance requirements (electrochemical interfacing with the brain, MEMS-based implantable 2-D and 3-D recording platforms, neural amplifiers and data converters, and downstream data storage, processing and analysis), and how scaling and integration can create powerful new devices and applications that significantly advance our understanding of the brain and neurological conditions or diseases. Examples of recordings in the rodent brain will highlight the unique capabilities of our nanofabricated approach to large-scale brain interfaces.

High-Voltage Organic Thin Film Transistor

4.07

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Sponsorship: DARPA

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Organic-based thin film transistors (OTFTs) are excellent candidates for flexible electronics due to their potential large area and room temperature depositions. OTFTs can be integrated with wearable electronics such as artificial skin or sensor-enhanced prosthetics. However, enabling truly ubiquitous electronics through OTFTs demands not only a high performance, but also a wide range of operating voltages. Many applications demand a high operating voltage beyond that capable of typical thin film transistors. For example, ferroelectric liquid, electrophoretic or electro-optic displays, digital x-ray imaging, poly-Si cold cathodes, and other sophisticated integrated microelectromechanical systems (MEMS) require large operating voltages to function.

In this work, we are developing a high-voltage organic thin film transistor (HVOTFT) based on the organic semiconductor 6,13-Bis(triisopropylsilylethynyl)pentacene (TIPS-PEN, $C_{44}H_{54}Si_2$), operable at several hundreds of volts. The design of the HVOTFT is based on a bottom contact architecture with organic compatible dielectrics. The TIPS-pen is drop casted on top of the contacts to form the active thin film. The key design structure is to implement an ungated region in series with the traditional gated region. The gated region allows for transistor switching behavior, while the ungated region enables the high voltage operation by acting as an effective resistor.

The device has been successfully fabricated on glass and flexible polyimide substrates. Currently, devices exhibit excellent performances with carrier mobilities of ~0.01 $cm^2/V{\cdot}s$, flexibility tolerance up to 1.5 inch radius of curvature, and operating voltages beyond 300 V. Although devices exhibit short channel and impeded charge injection, the addition of field plates have been promising in mitigating these effects. Our recent work involves introducing hydrophobic surface assembled monolayers to help assist the crystal growth in specific regions.

Fabrication of a Nanoporous Membrane Device for High Heat Flux Evaporative Cooling

4.08

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We investigated the experimental performance of a nanoporous membrane for future ultra-high heat flux dissipation from high performance integrated circuits for comparison to modeled behavior. The biporous evaporation device utilizes thermally-connected, mechanically-supported, high capillarity membranes that maximize thin film evaporation and high permeability liquid supply channels that allow for lower viscous pressure losses. The 600 nm thick membrane was created on a silicon on insulator (SOI) wafer, fusion-bonded to a separate wafer with larger liquid channels. Spreading effects and overall device performance arising from non-uniform heating and evaporation of methanol was captured experimentally. Heat fluxes up to 412 W/cm^2, over an area of and with a temperature rise of 24.1 K from the heated substrate to ambient vapor, were obtained. These results are in good agreement with a high-fidelity, coupled fluid convection, and solid conduction compact model necessitated by computational feasibility, which incorporates non-equilibrium and sub-continuum effects at the liquid-vapor interface. This work provides a proof-of-concept demonstration of our biporous evaporation device. Simulations from the validated model, at optimized operating conditions and with improved working fluids, predict heat dissipation in excess of 1 kW/cm^2 with a device temperature rise below 30 K, for this scalable cooling approach.

Miniature 3-D Printed Diaphragm Vacuum Pump

4.09

A. P. Taylor, L. F. Velásquez-García
Sponsorship: Edwards Vacuum

Miniaturized pumps supply fluids at precise flow rates and pressure levels in a wide variety of microfluidic systems. In particular, microfabricated positive displacement pumps that exploit gas compressibility to create vacuum have been reported as a first pumping stage in non-zero flow, reduced-pressure miniaturized systems, such as mass spectrometers. However, the mass flow rate versus pressure performance of positive displacement vacuum pumps manufactured with standard microfabrication is limited by their large dead volume compared to the total pump volume. Moreover, their expensive manufacture is incompatible with low-cost applications. Compared to standard microfabrication, additive manufacturing offers the advantages of rapid prototyping, larger displacements for better vacuum generation and larger flow rate, freeform geometries, and a broader material selection.

We report the first demonstration of a fully additively manufactured, miniature diaphragm vacuum pump. Using polyjet 3-D printing technology with 42 µm XY pixelation and 25 µm layer height, a single-stage vacuum pump design with active valves that has 1 cm^3 in total pumping volume and 5% dead volume was implemented. While operating at 3.27 Hz, the devices consistently pumped down from atmospheric pressure to 330 Torr in under 50 seconds (8.7 cm^3/min effective flow rate), which is >300X the highest reported flow rate from a diaphragm vacuum pump manufactured with standard microfabrication. Finite element analysis of the pump design estimated the maximum stress on the piston diaphragm root at full actuation at 100 kPa, and the natural frequency of the compression chamber at 42 Hz. Compression chamber diaphragms exhibited lifetimes approaching 20,000 cycles, while the valves membranes have not leaked after >1-million cycles.

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MEMS Energy Harvester for Low-Frequency, Low-Amplitude Vibrations

4.10

R. Xu, S. Xu, H. Akay, S.-G. Kim
Sponsorship: MIT-SUTD International Design Center

Harvesting energy from wide-band, low-frequency, and low-amplitude ambient vibrations at MEMS scale is promising but challenging. We have broadened the bandwidth of MEMS harvesters an order of magnitude by introducing nonlinear resonance in previous work, but the working frequency range and amplitude are still much higher than those of most ambient vibrations (below 100Hz and 1g). We have intentionally introduced buckling into MEMS clamped-clamped multi-layer plate structures to shift the working frequencies to a lower range at low excitation amplitudes. With an electromechanical lumped model, multi-layer beams could be designed to achieve bi-stability with desired frequency range and excitation amplitude. The MEMS devices could then be implemented by balancing the residual stresses in micro-fabricated thin films and controlling the thicknesses and stresses to achieve overall compression beyond critical buckling point. At the size smaller than a quarter coin, rectangular multi-layer plates based MEMS mechanical oscillators have been fabricated and tested to verify the frequency range at low excitation amplitudes. The prototype showed wide-band response with one order of magnitude lower frequency range (70Hz to 140Hz) at low excitation amplitude of 0.2g. A new fully functional prototype with piezoelectric elements embedded with improved design has also been fabricated and being tested.

Terahertz Beam-Steering Imager Using a Scalable 2D-Coupled Architecture and Multi-Functional Heterodyne Pixels

4.11

G. Zhang, J. Holloway, C. Wang, R. Han

Sponsorship: MTL

Terahertz (THz) imaging has important applications in industrial product inspection for quality control through material detection for security screening and environmental sensing for automotive driving. However, there do not exist any THz imaging systems that provide both high spatial resolution and high imaging speed at the same time. We propose to solve this problem by using a beam-steerable large scale on chip imaging array. The large scale gives us narrow beam-width thus high resolution and beam-steering results in high speed.

We have designed an on-chip 280GHz heterodyne imaging array in our lab using 130-nm SiGe BiCMOS (f_T/f_{max}=300GHz/500GHz) technology. The array is highly scalable due to a de-centralized array architecture with LO-integrated pixel design. The heterodyne scheme gives phase information for digital beam scanning.

Each pixel is highly compact and multifunctional by using the orthogonality of different modes of electromagnetic (EM) wave. Local oscillation, THz wave reception and heterodyne detection are realized in each pixel with only two transistors and a DC power of 10mW. The simulated sensitivity of each pixel is 2.9pW (BW=1kHz), which is ~25x higher than prior art.

On the array level, the LO phase noise improves with the array scale and reaches -101dBc/Hz (@ Δf =1MHz) with 32x32 pixels. We also achieve a 3dB-beamwidth of 5 degrees.

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Synthetic Butterfly-Inspired Scale Surfaces with Tunable Compliance and Anisotropic Droplet Adhesion

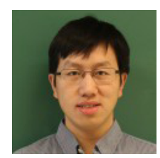
4.12

H. Zhao, S. J. Park, B. R. Solomon, S. Kim, D. Soto, A. T. Paxson, Y. Zou, K. K. Varanasi, A. J. Hart

Sponsorship: Air Force Office of Scientific Research, NSF

Many natural surfaces such as butterfly wings, beetles' backs, and rice leaves exhibit directional liquid adhesion or transport; this is of fundamental interest as well as for applications including self-cleaning surfaces, microfluidic devices, and phase change energy conversion. For example, the intricate scales on the wings of the *Morpho aega* give rise to hydrophobicity and anisotropic droplet roll-off behavior. Previous studies have explained anisotropic roll-off, for example, via the directionality of a rigid ratchet surface or the re-arrangement of nanoscale tips. Inspired by the butterfly wing, we demonstrate the fabrication of flexible synthetic scale surfaces from arrays of thin carbon nanotube (CNT) microstructures. Uniform centimeter-scale arrays of CNT scales are synthesized by a strain-engineered chemical vapor deposition (CVD) technique, using an offset-patterned catalyst layer that imparts a spatial gradient in the CNT growth rate, causing the scales to curve during growth. The scale height and curvature are controlled via the CNT growth parameters. After growth, the scales are conformally coated with a thin ceramic layer (i.e., Al_2O_3, by atomic layer deposition) followed by a hydrophobic polymer (divinylbenzene, by CVD) to tune their compliance and surface wettability.

We demonstrate that the CNT scales exhibit anisotropic droplet roll-off, and via high-resolution optical imaging, we observe how the droplet pinning and motion are influenced by the scale geometry and flexibility. The electrical conductivity and mechanical robustness of the CNTs, and the ability to fabricate complex multi-directional patterns suggest further opportunities to create engineered scale surfaces.



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Thermal Runaway Due to Negative Differential Emission from Ultra-Thin Vanadium Dioxide

5.01

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Sponsorship: DOE, Office of Basic Energy Science

Thermal runaway is a well-known phenomenon that occurs when a rise in system temperature leads to an event that promotes a further increase in its temperature. In a system dominated by radiation losses, thermal runaway is expected if the optical properties have a particularly strong temperature dependence, which is discussed in this work. We studied the thermal emission through an ultra-thin film vanadium dioxide structure which undergoes an insulator-to-metal phase transition at ~340 K, causing a sufficiently drastic reduction in the hemispherical emittance of the film. This property was exploited in order to directly demonstrate broadband negative differential emittance, as evidenced by a thermal runaway phenomenon. We characterized this phenomenon using a lumped thermal capacitance model to explore the limiting behavior and discuss tunability of the transient response. If understood and controlled, thermal runaway opens up the door for improving micro-scale thermal measurement devices such as microbolometers, heat flux calorimeters, etc.

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An Integrated Microcombustor and Photonic Crystal Emitter for Thermophotovoltaics

5.02

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Sponsorship: Institute for Soldier Nanotechnologies

Thermophotovoltaics (TPV) are a method of millimeter-scale power generation that promises energy densities greatly exceeding that of lithium ion batteries. In our TPV experiment, propane and oxygen react in a microcombustor to heat a photonic crystal emitter to incandescence and the resulting spectrally-confined radiation drives low-bandgap photovoltaic cells to generate electricity. The microcombustor, photonic crystal emitter, and the interface between the components are subjected to high temperatures (>1000 C) for a long operation lifetime, rapid thermal cycling, and thermomechanical stresses arising from differing thermal expansion. The previous method of integrating the microcombustor and photonic crystal by welding was proved unsatisfactory.

This work presents a new fabrication method for integration of the Inconel microcombustor and tantalum photonic crystal emitter. We adopted the industrial process of diffusion brazing, in which the addition and subsequent diffusion of melting point depressants out of the brazing alloy increases its remelt temperature. Thus, the brazed joint can be reliably operated above the original brazing temperature. Not only does diffusion brazing offer a stable interface with excellent thermal conductivity, it also offers faster and lower cost fabrication compared to welding. Although other technical barriers remain to be overcome to realize full performance in a portable device, diffusion brazing represents a breakthrough in fabrication and integration.

Nanopatterned Carbon Nanotube Surfaces for Stable Selective Absorbers and Emitters at High Temperatures

5.03

K. Cui, P. Lemaire, H. Zhao, T. Savas, C. Jacob, G. Parsons, A. J. Hart

Sponsorship: NSF, MIT Energy Initiative

Solar thermophotovoltaic (STPV) systems rely on an engineered nanophotonic absorber/emitter surface to convert broadband sunlight to narrow-band thermal emission for band-matching photovoltaics. The engineered nanophotonic layer is composed of periodic arrays of nanocavities, which can tailor thermal radiation. Recent research has focused on absorber/emitter fabrication by nanopatterning of refractory metals based on lithography and lengthy reactive ion etching processes. The manufacturing complexity significantly limits the scalability of nanophotonic absorber/emitter surfaces. Moreover, refractory metal-based nanophotonic surfaces suffer from severe surface diffusion and structural degradation, causing loss of selectivity in solar absorption and thermal emission. Thus, the long-term thermal stability at high temperatures is another issue that limits the widespread applications of STPV systems.

Carbon nanotubes (CNTs) are potentially attractive for use in TPV systems because of their high melting temperature (exceeding 3,500 K under inert atmosphere) and surface stability. Moreover, CNTs can be manufactured by scalable chemical vapor deposition (CVD) methods. Here we propose a tungsten-CNT nanostructure, where CNTs serve as scaffold to maintain the integrity of the nanostructure at high temperatures. We carried out the fabrication and characterization of nanopatterned W-CNT surface, with 500 nm diameter cylindrical cavities and 650 nm spacing. The surface was designed using ab-initio FDTD calculations (physical parameters obtained from Lorentz-Drude model). The nanopatterned catalyst layer for CNT growth was realized using interference lithography. After the CNT growth, the nanopatterned CNT surface was coated with Al_2O_3 and W by atomic layer deposition (ALD). We also investigated the thermal emission spectrum and thermal stability of the nanopatterned W-CNT surface.

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Retention of Droplets with In-situ Precipitation

5.04

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Sponsorship: MIT Tata Center for Technology and Design

Poor retention of agricultural sprays on hydrophobic plants is an important issue, as large quantities of toxic chemicals end up in soils and groundwater after sprayed droplets bounce off leaves. Here we propose to increase liquid retention on hydrophobic surfaces by in-situ formation of hydrophilic surface defects that pin the impacting drops. Defects are formed through simultaneous spraying of solutions containing opposite polyelectrolytes, which combine on the surface and precipitate.

We study individual drop-on-drop impact dynamics with high-speed imaging and analyze the surface after impact. Using these results, we elucidate the mechanism of precipitate formation and droplet retention. We derive a physical model to estimate the energy dissipation by the formed defects and compare it to the kinetic energy to predict the transition from bouncing to sticking, which can be used to design effective sprays. We finally show large macroscopic enhancements in retention of sprays on superhydrophobic synthetic surfaces as well as leaves.

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High-resolution Optical and Structural Characterization of InGaN/GaN Quantum Well LEDs to Reduce Efficiency Droop

5.05

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Sponsorship: Department of Energy

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InGaN/GaN quantum well (QW) LEDs are promising for full-color displays due to the ability to tune the band gap across the visible spectrum by controlling In content in the active layers. However, InGaN LEDs suffer from severe efficiency droop, in which the quantum efficiency peaks at low injection currents and decreases monotonically with increasing current. For commercial InGaN blue LEDs, peak external quantum efficiency of 65% is achieved at a drive current of 10 A/cm^2 but drops to 56% at 100 A/cm^2. In order to become practical sources of lighting on a large scale, the high-current efficiency of InGaN LEDs must be dramatically improved.

Here, we correlate luminescence of InGaN/GaN QW structures to non-uniformities in the QWs including defects, compositional fluctuations, and well-width fluctuations (WWFs). A widely accepted mechanism for efficiency droop is increased Auger recombination in regions of localized carrier concentration. While increasing In content allows for band gap tunability and mitigates droop, it also increases crystalline defects and In segregation within the QWs, both of which localize carriers and lead to enhanced Auger and Shockley Read Hall recombination.

We use high-resolution scanning transmission electron microscopy (STEM) to identify WWFs and defects, and electron energy-loss spectroscopy (EELS) to identify compositional fluctuations by examining the energy and intensity of In and Ga volume plasmon peaks. STEM-cathodoluminescence (STEM-CL) allows for nanometer-scale correlation of non-uniformities to light emission. We plan to map structural and compositional fluctuations on the nanometer scale to obtain a complete picture of the relationship between optoelectronic properties and structure of QWs, allowing the design of growth processes for InGaN LEDs to be theory-driven rather than empirically-driven.

In-situ Optical and Electronic Characterization of Organic-Inorganic Perovskite Materials

5.06

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Sponsorship: Eni S.p.A.

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Organic-inorganic perovskite solar cells have recently experienced an incredible rise in power conversion efficiency reaching performance levels similar to the leading commercial photovoltaic materials. However, one of the largest barriers to the commercialization of these perovskite materials in photovoltaic applications is their instability, which can be related to internal processes such as ion migration throughout the perovskite film.

We first study the effects of ion migration on the nanoscale optical properties of $CH_3NH_3PbI_3$ films using cathodoluminescence in scanning transmission electron microscopy (CL-STEM) and show that strongly luminescent nanoscale areas correspond to iodide-enriched regions. We then use electron beam induced current (EBIC) to study the effect of voltage biasing on the ion migration and resulting changes in current extraction. By biasing devices in-situ, we compare nanoscale inhomogeneities in current extraction before and after forward biasing and use both the dark and electron beam induced current transients to understand the underlying processes which change device operation after biasing. These studies allow us to directly understand the role of voltage biasing and ion migration in both performance improvements and long term degradation of perovskite solar cell devices and ultimately in the improvement of the device performance and stability.

Dropwise Condensation of Low Surface Tension Fluids on iCVD Grafted Polymer Films

5.07

K. Khalil, D. Soto, K. K. Gleason, K. K. Varanasi

A large majority of the work devoted to surface engineering for promoting dropwise condensation heat transfer has focused on steam. Much less attention has been dedicated to the condensation of low surface tension fluids such as hydrocarbons, cryogens, and fluorinated refrigerants, which are used in several industrial applications, including LNG storage and organic Rankine cycles used for heat recovery from low temperature sources such as biomass combustion, industrial waste, or geothermal heat sources. Most hydrophobic modifiers used previously to promote dropwise condensation are silane-based monolayers that have been shown to rapidly degrade under industrial conditions. Here we investigate condensation behavior of a variety of low surface tension liquids on durable covalently-grafted polymer films deposited using initiated chemical vapor deposition (iCVD) on metals such as titanium and stainless steel. We observe a four to seven-fold improvement in the vapor-side heat transfer coefficient by promoting dropwise condensation of low surface tension fluids on these stable films.

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Large Scale Broadband Acoustic Energy Harvesting Via Synthesized Negative Impedance

5.08

N. Monroe, J. H. Lang, A. P. Chandrakasan

Sponsorship: Ferrovial, S.A.

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 cm 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 arbitrary 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 Thevenin 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, in essence, the parallel combination of a resistive impedance and negative capacitive and inductive impedances. We realize this load losslessly (in theory) using a power factor correction-like switched H-bridge circuit, with control algorithms to force a transfer function impedance of voltage and current. 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.

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Thermal Management in GaN HEMTs via Wafer Bonding

5.09

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Sponsorship: Masdar Institute, Office of Naval Research PECASE Award Supervised by Dr. P. Maki

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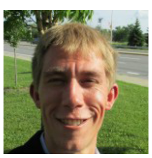
Gallium nitride (GaN)-based high electron mobility transistors (HEMTs) offer excellent performance in power conversion and high frequency power amplification. However, device self heating reduces output power to 1/8th of reported maximums. Device level thermal management is, therefore, critical for reliable high power operation. While incorporating thermally conductive substrates such as Silicon Carbide (SiC) and diamond has improved thermal performance, our simulations show that dislocated, low quality GaN buffer layers contribute significantly to the overall thermal resistance. By eliminating these thermally resistive materials, we can improve reliability and maximum operating power. Using wafer bonding, we have developed a novel GaN-on-SiC HEMT which eliminates this thermally resistive material and places the device in close proximity to the thermally conductive SiC substrate. An analytical comparison of our structure and standard GaN-on-SiC and GaN-on-diamond HEMTs yields a respective 20% and 15% reduction in peak temperature rise at a 5 W/mm power density.
Our fabrication approach involves direct bonding and transferring a GaN-on-Si HEMT epitaxy to a new SiC substrate. Subsequent removal of the original Si substrate and the highly dislocated buffer layers yields the near-substrate GaN/AlGaN heterostructure. So far, we have achieved reliable GaN-SiC bonding via surface activated bonding and high temperature annealing in specialized fixtures. This work is the first time a GaN transistor structure has been directly bonded to a SiC substrate. Current work is focused on refining the Si and GaN buffer removal needed to fabricate HEMTs. Next steps include thermal resistance measurements of the bonded structure and test device fabrication. We believe wafer bonding is a promising and general technique to reduce the near-junction thermal resistance of GaN HEMTs and unlock their full electrical performance.



Scalable Nanoporous Silicon for Applications in Water and Energy

5.10

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Available from June 2018.

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Nanoporous silicon (NPSi) membranes have recently received significant attention for their utility in a wide variety of applications, from filtration of water and other media to energy generation and storage. Though a plethora of fabrication techniques developed by the semiconductor industry have been applied for the fabrication of NPSi, a lack of processes which are both capable of reaching the nanometer feature sizes desired while still being scalable is preventing the implementation of NPSi in the aforementioned sectors.

Here we explore the scalable and economical fabrication of NPSi via a modified metal-assisted chemical etching (MACE) technique. Standard MACE involves the use of noble metal features deposited on a silicon substrate to electrochemically catalyze the reduction of hydrogen peroxide in solution, resulting in the injection of a hole into the substrate, which is oxidized and etched by hydrofluoric acid. Catalysts are drawn via van der Waals forces in the direction of etching, allowing for a continuous and anisotropic process. Despite a recent focus on the use of nanoparticle catalysts for the etching of nanopores in silicon, particle aggregation and lack of directional control in the etching process have hampered the production of NPSi with well-spaced, homogeneously sized nanoscale pores.

The modified MACE process presented here is introduced with the goal of overcoming these challenges to yield viable nanoporous membranes. A silica shell is employed as a sacrificial spacer layer surrounding a gold core. The composite nanoparticles are allowed to self-assemble from solution into close-packed monolayers on the sample surface. Immersion in the MACE etchant results in the consumption of the silica shell followed seamlessly by the etching of individual sub-10 nm pores. The fine degree of control in the particle synthesis process translate to a novel degree of pore size and spacing control over large areas.

Graphene Perovskite Schottky Barrier Solar Cells

5.11

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The sun radiates up to 1 kW of power per square meter onto the earth's surface. Solar cells capture this light energy and convert it into useable electricity. However, satisfying the rapidly increasing world energy demand using conventional photovoltaics can be prohibitively expensive. Solar cells typically comprise an active layer, which absorbs incident light and converts it into carriers, and a transparent electrode, which is responsible for collecting these carriers. Lead halide perovskites are an emerging class of active layer materials that offers high power conversion efficiencies and low material costs compared to other thin-film technologies. Graphene, being optically transparent and electrically conductive, is a novel transparent electrode with advantages in cost, weight, and flexibility. Combining these two synergetic technologies can significantly reduce the cost and complexity of solar cells.

In this work, we deposit perovskite films directly onto graphene to fabricate graphene/perovskite Schottky barrier solar cells. Spin-coating perovskite precursor solutions onto graphene is challenging because graphene is hydrophobic, but we circumvent this difficulty using solvent modification. The mismatch in work function between the graphene and perovskite generates an electric field at the interface that is responsible for collecting photo-generated electron hole pairs. Although hole transport layer-free perovskite solar cells have been reported in the past, this is the first demonstration of a Schottky barrier-based perovskite solar cell. The maximum power conversion efficiency achieved is about 11%, compared to 13% for reference devices with conventional topology. Our results also suggest that the operating mechanism of perovskite solar cells is free charge carrier generation rather than exciton generation.

Fabrication of an Omnidirectional 2D Photonic Crystal Emitter for Thermophotovoltaics

5.12

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Two-dimensional photonic crystals (PhCs), used in thermophotovoltaic (TPV) systems for efficient heat to electricity conversion, offer high in-band emissivity and low out-of-band emissivity at normal incidence, but have reduced in-band emissivity off normal. An omnidirectional PhC capable of high in-band emissivity at all angles would increase total in-band power by 55% at 1200°C. In this work, we fabricate and characterize an omnidirectional hafnia-filled 2D tantalum PhC emitter suitable for TPV applications such as combustion, radioisotope, and solar TPV. The work builds on a previously developed fabrication process to produce a square array of cylindrical cavities in a metal substrate and on the previously published theoretical simulations of filled PhCs.

In both our filled and unfilled 2D PhCs, the emissivity of the substrate material is selectively enhanced to near that of a blackbody emitter by the resonant cavity modes resulting from the etched holes. The spectral range of enhancement can be easily tailored to the specific system needs by tuning the geometric parameters of the cavities to match different PV cell bandgaps. This simple geometry increases high temperature stability and enables relatively simple fabrication of large area samples. In the filled cavity PhC, a high-index dielectric material enlarges the optical size of the cavity. Thus, the radius and period of the filled PhC is about half of that of the unfilled PhC to achieve the same cutoff wavelength. Dielectric filling improves the hemispherical performance without sacrificing stability or ease of fabrication.

This work is the first experimental demonstration of a 2D dielectric-filled metallic PhC selective emitter for TPV energy conversion systems. We present numerical simulations, fabrication processes, and optical and thermal characterizations of the PhC.

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Low Roughness Silver Nanowire Electrodes for Flexible Solar Cells using Fully Scalable Processes

5.13

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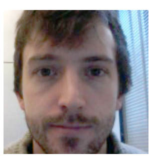
Sponsorship: Tata Center for Technology and Design

Large area, flexible third generation solar cells are a good candidate for worldwide electrification. However, in order to achieve a robust, flexible solar cell, some engineering challenges still need to be overcome. One such challenge resides in the use of vacuum processed transparent conducting oxides. Industrial scale conducting metal oxides tend to crack when placed on flexible substrates, limiting their use and increasing failure modes in the final solar cell structure. Metal nanowire meshes are a scalable replacement but suffer from oxidation and high surface roughness which limits their use in modern thin film solar cells. Here we explore a fabrication technique that utilizes solution processed spray coating, low vacuum CVD, and a plastic lamination process to create a low cost Silver Nanowire/Parylene/PET composite that has low surface roughness (<3 nm RMS) and is compatible with modern solar cell technology. Not only is this composite electrically and optically comparable to conducting metal oxides, it entirely uses low cost materials and low CapEx processes, making this composite a candidate for high throughput manufacturing.



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Comprehensive Study of Thin Film Evaporation from Nanoporous Membranes for Enhanced Thermal Management

5.14

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Sponsorship: Masdar Institute of Science and Technology, Abu Dhabi, UAE

Performance of emerging electronics is often dictated by the ability to dissipate heat generated in the device. Thin film evaporation from nanopores promises enhanced thermal management by reducing the thermal transport resistance across the liquid film while providing capillary pumping. We present a study of the dependence of evaporation from nanopores on a variety of geometric parameters. Anodic aluminum oxide membranes were used as an experimental template. A biophilic treatment was also used to create a hydrophobic section of the pore to control meniscus location. We demonstrated different heat transfer regimes and observed more than an order of magnitude increase in dissipated heat flux by confining fluid within the nanopore. Pore diameter had little effect on evaporation performance at pore radii of this length scale due to the negligible conduction resistance from the pore wall to the evaporating interface. The dissipated heat flux scaled linearly with porosity as the evaporative area increased. Furthermore, it was demonstrated that moving the meniscus as little as 1 um into the pore could decrease performance significantly. The results provide a better understanding of evaporation from nanopores and provide guidance in future device design.

Optimally Harvesting Power From Multiple Vibration Frequencies Simultaneously

5.15

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Harvesting ambient vibration energy through piezoelectric (PZ) Energy Harvesting Devices (EHDs) can provide power for low-power wireless sensor nodes. In order to maximize harvested power at a single frequency, a high-Q resonator is required. As a result, output power drops dramatically as the source vibration frequency deviates from the resonant frequency. In earlier research, we have shown that the resonance frequency can be tuned using an electronic circuit called Bias Flip. This allows us to achieve near-optimum output from a single frequency, even if the frequency deviates from the mechanical resonance frequency of the EHD. However, in practical applications, the source vibration often has multiple frequencies which may vary with time. The current research that will be reported at MARC2017 addresses the challenge of optimally harvesting power from a vibration source having multiple vibration frequencies. This work extends the Bias Flip technique to multiple vibration frequencies. We theoretically calculate harvested power for multiple frequencies and compare this to the theoretical maximum power. Harvested power is calculated using different Bias Flip algorithms and varying Bias Flip efficiency. The next step is to experimentally demonstrate the theory.

Conformal Electroplating of Azobenzene-Based Solar Thermal Fuels onto Large Area and Fiber Geometries

5.16

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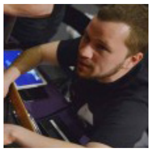
There is tremendous growth in fields where small functional molecules and nanomaterials act as the key component of energy devices, which often requires the fabrication of thin-films for incorporation into the solid-state. Notably, many of such constituents are synthesized in solution and there often exists a significant barrier to transitioning them to the solid-state in an efficient and versatile manner. In our present work, we report a co-polymer electrodeposition method that is applicable to a wide scope of small molecules for energy applications and provides unprecedented flexibility for their incorporation into the solid-state. This novel approach is applicable to systems such as photon upconversion, micro-switches, micro-actuators, photovoltaics, photosensing, light emission, solar thermal fuels and beyond.

We have focused on recently reported solid-state solar thermal fuels that have tremendous potential as materials that can both harvest and store solar energy. We design a novel co-polymer employing charging units that may be electrodeposited onto a variety of substrates with three-dimensional geometries. This approach also enables us to envision novel implementations of solar thermal fuels into solar thermal fibers that may be employed in fabrics, which are successfully demonstrated using our method. Importantly, the co-polymer method allows for excellent retention of the small-molecule properties and presents a robust avenue to forming solid-state films with minimal compromises.

These novel solar thermal fuel materials exhibit solid-state UV chargeability, thickness tunability from hundreds of nanometers to tens of microns, exceptionally high materials utilization efficiency, a gravimetric energy density of approximately 100 J/g (~28 Wh/kg), and the ability to be deposited on a wide range of structured conducting substrates.

We see this work as an important milestone for transitioning small-molecule energy materials in an efficient and versatile way into the solid-state, offering additional processing and cost saving benefits.



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Large-Scale Optical Characterization of Quantum Emitters in Nanostructures for Quantum Repeaters

6.01

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Sponsorship: NASA Space Technology Research Fellowship

The nitrogen vacancy (NV) center in diamond is a leading memory candidate for future applications in quantum computing and the development of quantum repeaters. The NV center has a number of advantages, ranging from its long coherence times to its potential for efficient scaling in larger architectures. One weakness, however, is its optical properties, with only 3% emission into its coherent zero phonon line. Furthermore, the high index of diamond means that total internal reflection sharply limits the spatial collection efficiency of simple confocal microscope setups.

Fabrication of nanostructures such as photonic crystal cavities and nanowire waveguides is one direction towards improving upon these spectral and spatial inefficiencies, and in particular, paves a path towards scalable, on-chip integration of multiple NV systems. However, the inherently stochastic nature of nanofabrication requires the creation of many copies of devices for every single good one. Furthermore, the fabrication process is often destructive to NV centers, requiring even more overhead to generate a device that both meets design specifications and has a functioning NV inside. We introduce a large-scale cryogenic screening method that allows us to characterize the optical properties of hundreds to thousands of quantum emitter systems autonomously. This technique is applied to NVs in diamond nanostructures to prescreen for devices with strong emitter-cavity coupling, long coherence times, and narrow linewidths. Once located amongst the thousands of candidates, these highest performing devices can be integrated into a larger chip infrastructure for building scalable systems like quantum repeaters.

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Mode-Evolution Based Coupler for Ge-on-Si Photodiodes

6.02

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Sponsorship: DARPA

Light detection is an important aspect in many integrated photonic systems. Various techniques have been investigated for this purpose such as bonding III-V photodetectors to silicon wafers. In contrast to bonding, the successful development of germanium growth on silicon has shown that germanium-on-silicon (Ge-on-Si) photodetectors are a viable option for near-infrared detection in a complementary metal-oxide-semiconductor compatible platform. Such devices have been studied extensively with efforts focused on improving the performance of butt-coupled Ge-on-Si photodetectors. However, the electrical output of such devices saturates when illuminated with a high power optical input signal.

We have developed a novel light coupling scheme for Ge-on-Si photodetectors based on the principle of mode-evolution, which greatly reduces the saturation effects observed in similar sized butt-coupled detectors. Specifically, using this new coupling method, we show a 70% increase in photocurrent generation under high power illumination. This type of coupling scheme for Ge-on-Si detectors can be useful for many integrated optical systems including microwave photonics, optical communications and optical sensing that demand both high-power and high-speed devices.

Waveguide-Integrated Graphene Photodetectors on a Foundry CMOS Platform and for Mid-IR Detection

6.03

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Sponsorship: National Science Foundation, Office of Naval Research

Graphene's unique optoelectronic properties have spurred interest in a range of photodetection applications. Here we present research on incorporating high-responsivity, high-speed graphene photodetectors on photonic integrated circuits.

First, we demonstrate progress towards a waveguide-integrated graphene detector on a zero-change commercial foundry CMOS chip. The silicon device layer of an SOI CMOS process is used to construct waveguides as well as electronics to amplify the photodetector signal. Removal of the silicon substrate and thinning of the buried oxide layer allows graphene to be placed within the waveguide mode as a post-processing step. To our knowledge, this would be the first demonstration of a waveguide-integrated graphene detector on a commercial CMOS chip and paves the way for integrated photonics based on graphene active devices.

Second, we demonstrate progress towards integration of graphene photodetectors with chalcogenide glass waveguides to detect light at a wavelength of 5.2 µm. Calcium fluoride is used as the substrate due to its transparency at the desired wavelength and its low refractive index. This research has applications in chip-integrated mid-IR spectroscopy, useful for medical chemical sensing.

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Design for Manufacturability (DFM) Models, Methods, and Tools for Silicon Photonics

6.04

G. Martinez, S. Elhenawy, D. Moon, D. S. Boning

Sponsorship: AIM Photonics

The desire for higher data rates, lower energy communication and information processing, and new optically-based functionality is drawing attention to silicon photonics technology where photons instead of electrons are used. In silicon photonics, technology from silicon integrated circuit (IC) devices is adapted to fabricate photonic components, and in integrated silicon photonics, both electrical and optical components are integrated on the same chip. In order to become a capable and cost effective process, the already existing silicon CMOS IC fabrication infrastructure should be used. However, a key challenge for the emerging silicon photonics industry is the lack of mature models, design for manufacture methods, and simulation tools for optical components that are compatible with commercial CMOS process steps.

Our goal is to develop key elements of a robust design for manufacturability (DFM) methodology for silicon photonics. This includes understanding and modelling of the various process variations, both systematic and random, at the wafer, chip, or feature scales and predicting their impact on both photonic device and circuit levels. These variation-aware models and methods will help enable tomorrow's silicon photonics designers to predict and optimize behavior, performance, and yield of complex silicon photonic devices and circuits, just as IC designers do today.

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Focusing Optical Phased Arrays in a Silicon Photonics Platform

6.05

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

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Radio-frequency (RF) phased antenna arrays have enabled the development and advancement of numerous applications such as radio transmitters, radar, television broadcasting, and radio astronomy. However, due to the relatively long wavelengths of RF frequencies, large-scale implementation of these arrays – necessary for generation of ultra-high resolution and arbitrary radiation patterns – is cumbersome and expensive. As a solution, optical phased arrays, operating at much shorter optical wavelengths and fabricated in integrated nanophotonics platforms, open up possibilities for large-scale applications in a variety of areas including three-dimensional holography, biomedical sciences, communications, ion trapping, and light detection and ranging (LIDAR).

Current on-chip demonstrations of optical phased arrays have enabled systems which form and steer a beam or project a radiation pattern in the far field of the array. However, many potential applications of phased arrays, such as optical trapping and lithography, require micron-scale high-intensity spots which are steerable and confined in three-dimensional space. In this work, we demonstrate a new type of on-chip optical phased array, inspired by Fresnel lenses, which focuses radiated light to a tightly-confined spot in the near field above the chip. This focusing phased array, fabricated in a CMOS-compatible process, consists of a splitter network which feeds an array of perturbation-based antennas with appropriate phase shifts. Additionally, we discuss application of the device to on-chip optical trapping for biological characterization and trapped-ion quantum computing.

A Terahertz Quantum Cascade Amplifier using an Adiabatic Integrated Horn

6.06

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Quantum Cascade Lasers (QCLs) have developed relatively quickly from an experimental demonstration in 1994 to initial commercial devices for mid-infrared applications in only 10 short years. QCLs have also shown great promise to be the dominant optical source for longer wavelength, Terahertz systems. This Terahertz frequency regime, from 1 THz to 10 THz, or wavelengths of 300μm to 30μm, has been notoriously difficult for device development. As a consequence, demonstrations of THz systems have been difficult to realize due to a scarcity of basic system building blocks.

One such system component that is still needed is a Terahertz amplifier, capable of amplifying free space radiation that is not contained within a waveguide. Such a device can be realized by using the active region of a Terahertz Quantum Cascade Laser (THz-QCL) to provide gain for the amplifier. For this amplifier, the nominal QCL laser cavity is modified to have higher mirror loss which will suppress lasing and increase coupling between cavity modes and free space radiation. To implement higher mirror loss and increased coupling, a three dimensional integrated horn is fabricated as part of the QCL cavity. In order for the horn to increase the mirror loss optimally, the cavity mode should be expanded as adiabatically as possible. This work demonstrates the design and fabrication of the integrated adiabatic horn and its effect on the operation of the THz-QCL Amplifier.

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

6.07

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Sponsorship: Office of Naval Research, MIT Lincoln Laboratory

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 and uniform electric fields at this scale due to divergence of the fields in dielectrics. This field divergence limits the gating strength, boundary sharpness, and pitch size of periodic structures, and restricts possible geometries of local gates (due to wire packaging), precluding certain device concepts, such as plasmonics and transformation optics based on metamaterials.

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 resist mask to locally create excess charges on top of the gated surface. Electrostatic simulations indicate high carrier density variations of $\Delta n = 10^{14}$ cm^{-2} across a length of 10nm at the mask boundaries on the surface of a 2D conductor, resulting in a sharp depletion region and a strong in-plane electric field of $6{\times}10^{8}$ V/m across the so-created junction. We apply this technique to the 2D material graphene to demonstrate the creation of tunable p-n junctions for optoelectronic applications. We also demonstrate the spatial versatility and self-aligned properties of this technique by introducing a novel graphene thermopile photodetector.

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Autostereoscopic Image Projection with a Nanophotonic Phased Array Grid

6.08

M. Raval, A. Yaacobi, M. R. Watts

Sponsorship: DARPA E-PHI Program

Incorporation of 3D display systems into mobile devices such as cellphones and tablets requires that these display systems have small form factors and high spatial resolution. The majority of 3D display systems and methods demonstrated to date require a system of bulk optics for relaying virtual images or lack sufficiently high resolution.

Here, we present a novel planar chip-scale autostereoscopic image projection method based on a grid of visible light nanophotonic phased arrays, each of which is passively configured with the necessary phase distribution for projecting a portion of the light field of the desired virtual object. The necessary partial light field projected by each phased array is determined by its physical location on the grid with respect to the virtual image. The presented system consists of a 1D grid of 16 phased arrays, each comprised of 1024 optical antennas and designed for operation at 635 nm, for projecting a virtual image with horizontal parallax.

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Fully Integrated CMOS-Compatible Q-Switched Laser at 1.9µm Based on Tm-Doped Al_2O_3

6.09

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Sponsorship: DARPA

We demonstrate a fully integrated on-chip Q-switched laser at 1.9µm, fabricated using a CMOS-compatible process. The laser is based on Thulium-doped aluminum glass used as a gain material, deposited on a silicon nitride-based waveguide platform. We have demonstrated lasing at an 1892nm wavelength with 1614nm pump and were able to obtain up to 4.5mW of on-chip laser power using 1W on-chip pump power. The lasing threshold was 200mW of pump power.

At about 700mW of pump power, the laser goes from continuous wavelength lasing regime to Q-switched regime, with a repetition rate of 560kHz. This repetition rate, with 4.5mW of average power, corresponds to 9nJ of pulse energy and is tunable depending on the input pump power. The laser cavity is designed to facilitate true mode-locking in addition to Q-switching.

Further improvements to the cavity are being made in order to achieve this fully on-chip integrated mode-locked laser. Theoretical simulations predict final pulse duration of 500fs when the laser goes into mode-locking regime. Except for the pump laser, all the laser cavity components are integrated – there are no off-chip elements.

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Electronics, GaN, III-Vs, integrated circuits, lasers, light-emitting diodes, MEMS & NEMS, microfluidic devices & systems, nanotechnology, optoelectronics, photonics, sensors, Si.

Development of a Heterogeneous Platform for Photonics and Bio-Optoelectronics Applications Including Standard Si (100) CMOS and Wide Bandgap

6.10

N. Vico Trivino, J. Scholvin, D. R. Englund, T. Palacios
Sponsorship: ONR PECASE Program

Wide bandgap III-nitride (III-N) semiconductors offer unique optical and electronic properties that make them ideal candidates for optoelectronics, high-power and high-frequency electronics. This is confirmed by the impressive market growth of such materials with the commercialization of white light-emitting diodes (LEDs) for solid state lighting and laser diodes (LDs) found, for instance, in data storage technologies. Thus, despite several technological challenges, III-Ns have become a solid semiconductor family only surpassed by silicon in terms of market and annual revenues.

Beyond a wide direct bandgap, III-Ns offer tunable emission (transparency) spanning the ultraviolet to near infrared spectral region and large second-order nonlinear susceptibility, which is crucial for the development of nonlinear optics. They also feature high electron mobility and velocity, which allows for the fabrication of high electron mobility transistors (HEMTs) with high cut-off frequencies and low-loss power switches, along with thermal robustness, excellent biocompatibility, chemical inertness, and mechanical hardness.

The aim of this project is the implementation of a seamless heterogeneous GaN-on-Si technology including both electronic and photonic circuits. Our approach relies on material transfer of GaN thin films grown on Si(111) to a Si(100)/SiO_2 wafer via bonding and etch-back of the original Si(111) substrate.

Such a hybrid platform will benefit from the properties of each semiconductor family, enabling the selection of the best material for each function and opening a wide range of new applications. A third level including two-dimensional materials, e.g. MoS_2, is also foreseen with immediate applications on lab-on-chip standalone biosensors. In this regard, GaN-on-Si microLEDs are being fabricated for optogenetic neural stimulation.

Fabrication of High Quality Quantum Emitters in Diamond Nanostructures

6.11

M. Walsh, M. Trusheim, H. Choi, E. Bersin, D. R. Englund

Sponsorship: CIQM, CDQI

The controlled creation of defect center-nanocavity systems is one of the outstanding challenges for efficiently interfacing spin quantum memories with photons for photon-based entanglement operations in a quantum network. We demonstrate two methods. The first being direct: maskless creation of atom-like single silicon-vacancy (SiV) centers in diamond nanostructures via focused ion beam implantation with less than 50nm positioning accuracy relative to the nanocavity. We extract close to lifetime-limited single-emitter transition linewidths down to 126MHz, corresponding to 1.4 times the natural linewidth.

The second method relies on autonomously imaging emitters and registering them relative to an on-chip coordinate system. The microscope takes advantage of a unique marker that encodes its spatial location on a sample. We are currently implementing a compound machine vision-Bayesian inference system to allow the microscope to navigate and map samples. This technique can be performed on a larger variety of emitters, as it does not require a focused ion beam. The repeatability of this method suggests an accuracy down to around 20nm.

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Communications, information processing, photonics, quantum devices.

UV and Visible Integrated Photonics for Addressing Trapped Ion Qubits

6.12

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Sponsorship: National Science Foundation, MIT Lincoln Laboratory

We present recent work on the optical addressing of ions in CMOS-fabricated 2D planar traps. Quantum information processing requires ion manipulation and readout, traditionally accomplished with free-space optics. Our approach utilizes integrated waveguides and optical components for ion addressing, greatly reducing system cost, complexity, and sensitivity to perturbations.

We demonstrate diffraction-limited focusing grating couplers in silicon nitride for individual ion manipulation in the visible spectrum, and silicon nitride-loaded lithium niobate resonators with quality factors exceeding 300,000 in the IR. Lithium niobate's high electro-optic coefficient makes this easy-to-fabricate dielectric platform very promising for active optoelectronic devices.

Atomic layer deposition (ALD) grown aluminum oxide is also developed as a viable material for CMOS-compatible low-loss waveguides and passive optical devices in the visible and UV spectrum. We explore the dependence of growth rate and bulk refractive index on ALD deposition temperature. We also investigate masks and etch chemistries for alumina that provide the high anisotropy and smooth sidewalls required for optical waveguides.

Finally, we present a coherent plan for constructing high extinction electro-optic modulators (>70dB) to control ion addressing beams.

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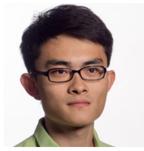

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Displays, light-emitting diodes, optoelectronics, organic materials.

High-Performance Inorganic $CsPbBr_3$ Perovskite Light-Emitting Diodes by Dual Source Vapor Deposition

6.13

S. Xie, A. Osherov, V. Bulović
Sponsorship: DOE Center for Excitonics

Organometal halide-based perovskites, with the typical chemical formula ABX_3, have emerged as a promising class of semiconducting materials for thin-film optoelectronics in the past few years. Those semiconductors possess unique electro-optical properties, such as long range carrier diffusion length, high absorption coefficients, and low levels of defect states, yielding solar cells with over 20% power conversion efficiency. While much of the research efforts have been captivated by the potential of their photovoltaic applications, perovskites are nonetheless promising light emitters.

Indeed, color-tunable electrically-driven perovskite light-emitting diodes (PeLEDs) have tremendous potential for novel display and lighting applications. In addition to its bright photoluminescence (PL) and excellent wavelength tunability, $CsPbX_3$ (X=I, Br, Cl) in particular exhibits superior thermal and chemical stabilities when compared to organic-inorganic analogs such as $CH_3NH_3PbX_3$. Unfortunately, low solubility limits of CsBr precursor hinder the fabrication of a dense, compact $CsPbBr_3$ layer with complete coverage and smooth morphology via solution processing. Incomplete coverage of perovskite emitting layer results in substantial leakage current that has limited the luminescent efficiency of previously reported cesium-based PeLEDs. Physical vapor deposition of fully inorganic $CsPbX_3$ perovskites offers a scalable alternative to solution processing.

In this work, we report a systematic approach for preparation of highly efficient $CsPbBr_3$ PeLEDs using vacuum deposition. Fabrication of $CsPbBr_3$ thin films with complete surface coverage and reduced roughness in addition to precise control over the film thickness, and stoichiometry is demonstrated. Perovskite films are optimized for the best device performance by varying parameters including evaporation rate, film thickness and composition of the as-deposited perovskite layer. As a result, $CsPbBr_3$-based PeLEDs that exhibit narrow green emission, significantly reduced leakage current, and therefore, substantially improved brightness and efficiency were realized.

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Modeling Exciton and Charge Dynamics in a Quantum Dot Light Emitting Diode

6.14

H. Zhu, V. Bulović
Sponsorship: DOE Center for Excitonics

Distribution of charges and their dynamics within a Quantum Dot Light Emitting Diode (QD-LED) strongly influences the operational behavior of the device. Charge imbalance in the quantum dot layer can quench luminescence if excitons are able to decay via Auger recombination. Strategies to combat this loss include using thick-shelled quantum dots that enable efficient luminescence from charged dots, inserting electron or hole blocking layers to adjust charge density, and tuning the dynamics of charges in the quantum dot layer via ligand engineering. However, the physics of exciton formation and the subsequent exciton dynamics in the presence of these charges has not been quantitatively modeled or systematically investigated experimentally.

Here we use three-dimensional kinetic Monte Carlo simulations to study a highly charged interface between the quantum dot layer and the neighboring hole transport layer, in which we explore the preferential formation of charged excitons as a function of various device parameters. This model is corroborated by temperature dependent spectroscopy of the device in operation and transient photocurrent measurements. Our results demonstrate how considerations of Coulombic interaction and charging energy can uncover new insights to the operation of a QD-LED. We anticipate that our modeling will allow future QD-LED design and optimization to be done in a more systematic manner.

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Research Interests:
Biological devices & systems, BioMEMS, medical devices & systems, microfluidic devices & systems, nanomanufacturing, nanomaterials, nanotechnology, optoelectronics, sensors, biopharmaceuticals, point of care applications, tissue Engineering, lab-on-chip, organ-on-chip.

Capture and Concentration of Pathogens in Chaotic Flows

7.01

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Sponsorship: MIT-Tecnológico de Monterrey Nanotechnology Program

Infectious diseases of both viral and bacterial origin continue to be a health threat to millions of people in developed and underdeveloped countries. One successful treatment strategy for cases of sepsis or viral infections is the effective capture and removal of the pathogenic agent from the bloodstream. We are presently developing filter-less technologies for the direct capture of bacteria (i.e., Escherichia coli) and eventually viruses (i.e., Ebola virus-like-particles).

We use a portable system for the capture of pathogens circulating through a microfluidic chamber. The system is based on the specific recognition of proteins on membranes or capsids; it integrates the use of (a) anti-pathogen polyclonal antibodies, (b) magnetic nanoparticles (MNP), (c) a microfluidic chaotic flow system, and (d) a neodymium magnet. Anti-pathogen antibodies are covalently immobilized within commercial magnetic nanoparticles to fabricate nanoparticles that will bind pathogens. Our experiments compare the performance of different immobilization strategies (amino-carboxylic covalent binding and streptavidin-biotin binding) and different magnetic nanoparticle sizes (range 30 nm - 800 nm). The heart and distinctive feature of our system is a microfluidic chamber in which the binding particles and the pathogen are mixed by the action of a laminar chaotic flow produced by the alternating rotation of two cylinders. The intimate contact induced by this chaotic laminar flow promotes the capture of the pathogen by individual nanoparticles or nanoparticle clusters. The trapped pathogens are then concentrated by a simple magnet located downstream from the microchamber.

This platform has key advantages over currently available methods, which are mostly based on the use of microfluidic channels or filtering membranes: (a) It is faster; (b) It offers superior capture due to the intimate mixing induced by the chaotic flow, and (c) it is easy to use.

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Design and Development of Flip-Chip Connectors for Multi-Functional Neural Probes

7.02

M.-J. Antonini, M. Kanik, A. Canales, P. Anikeeva

Sponsorship: NIH, Simons Center for the Social Brain

Recently developed polymer fiber based neural probes have enabled the multifunctional probing of brain and spinal cord circuits. These probes have a light-weight miniature design and contain optical waveguides, metal electrodes, and microfluidic channels. All of this makes these minimally invasive tools suitable for the probing of neural dynamics in acute and chronic experiments.

Fiber-based neural probes can be fabricated using the thermal size reduction technique by heating and stretching a macroscopic preform, which exhibits the same features as the targeted microstructured fiber probe. Although fiber-based neural probes with very complex 3D structures can be produced at scale, interfacing these devices to external electrical, optical, and microfluidic circuits remains an engineering challenge.

We demonstrate an interfacing technique that includes a design of custom connectors and a translational aligner system for electronically addressing each neural recording unit. By using scanning electron microscope images of the fiber cross section, we developed a series of four masks and five processing steps that enable transfer of the fiber electrode pattern into metallized through-holes on a matching connector. Other additional through-holes are created for the optical and microfluidic interfaces. Using custom designed flip-chips allows for scaling up the production of fiber based probes. Also, it enables the increase of spatial resolution and number of functional features within our probes. To enable facile alignment of fibers to the matching connectors, a custom aligner was designed and constructed. We demonstrate the utility of our connectorization approach by applying to fiber-based neural probes that feature nine metal recording electrodes with diameters of 8 µm positioned around a 300 µm hollow channel for drug delivery and optogenetic stimulation. A probe requires ~8 hours to connectorize manually, while the custom chip and aligner reduces this time to approximately 1 hour, enabling application of these probes in large-scale neuroscience experiments.

Evaluation of 3D-Printed Materials for Construction of Microfluidic Devices Intended for Biological Applications

7.03

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Sponsorship: Charles Stark Draper Laboratory

Microfluidic devices show promise as enablers of the exploration, development, and customization of medical treatments beyond traditional capabilities while saving time and cost. One such device, Draper's Personalized Predictive Assay for Cancer Therapy (PPACT), mimics interactions between tumors and the immune system in the human body, providing a microenvironment for testing the effectiveness of drugs. This microfluidic system is capable of testing treatments on tumors directly from the patient in a laboratory model to determine which therapies most effectively kill that patient's cancer. However, one of the principal barriers to broad application of microfluidic technologies in healthcare is related to the inherent challenges in device fabrication. Soft lithography approaches are generally restricted to simple geometries and a few material options, and are prone to large device-to-device dimensional variation.

Current manufacturing methods for complex microfluidic devices are technically challenging, time-intensive, and are constrained by existing microfabrication capabilities. In the present case, PPACT devices require a series of molding and assembly steps with associated tolerance and yield issues. Here, we report on an investigation of 3D printing technologies for fabrication of monolithic microfluidic devices that are transparent, non-cytotoxic, compatible with common disinfectants, and, in general, suitable for biological applications. 3D printing technologies have the potential to significantly reduce microfluidic part costs and fabrication times while maintaining a required level of device functionality. Additionally, 3D printing enables rapid iteration of device designs and construction of complex microchannel features that may otherwise be difficult, impractical, or unfeasible to attain. Future work will capitalize on the simplicity and versatility of 3D printing for manufacturing challenging device geometries.

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A Portable Bioimpedance Spectroscopy Measurement System for Congestive Heart Failure Management

7.04

M. Delano, C. G. Sodini

Congestive Heart Failure (CHF) is a chronic medical condition that causes reduced exercise tolerance, shortness of breath, and fluid buildup in the lungs, legs, and abdomen. The disease must be managed carefully to prevent hospitalizations. The standard of care for CHF management currently consists of some combination of daily weight monitoring, blood pressure monitoring and regulation, a low-sodium diet, diuretics to control fluid levels, and medications to improve heart function and reduce the impact of comorbidities. Patients may also receive implantable medical devices, such as a pacemaker or implantable cardioverter defibrillator (ICD), to minimize the impact of or eliminate arrhythmias.

While CHF-related mortality has reduced in recent years, this reduction has been accompanied by an increase in hospitalizations and readmissions. A home monitoring and management system for patients with CHF could help reduce the number of CHF-related hospitalizations and reduce the impact of CHF on the United States healthcare system. We have developed a portable (eventually wearable) bioimpedance spectroscopy system (BIS) to monitor fluid status levels of patients at the calf via a wearable compression sock. Our system has been evaluated in the lab and with healthy volunteers; we are in the process of testing the system alongside a commercial BIS system (SFB7) in the hemodialysis unit at MGH to measure volume change. A wearable CHF home management system that includes our BIS system, coupled with self-tracking tools and behavior change concepts, could empower patients to more easily manage their condition and reduce the likelihood of (re)hospitalization.

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Development of Minimally Invasive, Multi-Functional Neural Probes for Depth Specific Sub-Cortical Electrophysiological Recording

7.05

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Sponsorship: Simons Center for the Social Brain, NIH

Neural probe engineering is an emerging field for developing reliable, minimally invasive neural recording, stimulation, and drug delivery devices that can be used for in-vivo and in-vitro experiments. Implantation of neural probes made of hard materials, such as metal, glass, and silicon causes foreign body response in the brain, which often diminishes the quality of recordings in long-term experiments. Fundamental changes in fabrication technique and use of polymers have been recently implemented to address this problem. Thermal size reduction technique based on conventional fiber drawing is used to produce flexible fiber probes, which combine low-melting temperature metal electrodes for neural recording, polymer-based optical waveguides for optogenetic stimulation and microfluidic channels for viral vector and drug delivery. Development of these probes starts with the fabrication of a macroscopic preform, template of the desired probe design, in which refractive indices, conductivities, thermal expansion coefficients, glass transition and melting temperatures of the constituent materials play an important role. Following the preform fabrication and its consolidation under vacuum, the preform is heated above the glass transition and melting temperatures of its components and drawn into microscale fibers.

Here, we report a fiber neural probe with fine spatial resolution consisting of 6 individual multifunctional units for independent interrogation of neurons in different layers of cortex in an autism spectrum disorder (ASD) mouse model. The tip of this fiber probe is modified using ultra-microtome techniques so that each unit can probe different cortical layer. Each unit is equipped with metal electrode, optical waveguide, and microfluidic channel. Using this tool we aim to understand the electrophysiological signatures associated with structural abnormalities in somatosensory cortex in ASD mice.

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Research Interests: Biological devices & systems, BioMEMS, displays, medical devices & systems, MEMS & NEMS, microfluidic devices & systems.

High-throughput Label-Free Blood Cell Separation and Characterization using Dielectrophoresis

7.06

J. Lee, R. Yuan, Y. Fink, J. Voldman

Sponsorship: National Institute of Health, Defense Advanced Research Projects Agency, National Science Foundation, US Army Research Laboratory and the US Army Research Office through the Institute for Soldier nanotechnologies, Korea Foundation for Advanced Studies

Researchers have developed many methods to analyze or separate out specific blood cells with similar sizes like neutrophils from the whole blood since specific blood cells have important information. For example, when a patient suffers sepsis, the number of activated neutrophils sharply increases compared to non-activated neutrophils. The most common method to analyze and count specific blood cells is labeling cells by attaching markers such as magnetic or fluorescent markers. However, those markers may change the original characteristics of cells, which may affect diagnosis.

We develop microfluidic devices that use dielectrophoresis (DEP) to realize label-free cell sorting and analysis. By tuning the electrode structure and the conductivity profile of the medium, we can separate out and characterize specific cells from similar-sized cells without labeling. However, state-of-the-art DEP based cell sorting is relatively slow. Our goal is to increase the throughput of electrical sorting. By using a novel fiber-based channel structure, we are working to increase the throughput of electrical cell sorting devices. The ultimate goal is combining electrical sorting with other sorting modalities to realize all-in-one cell sorting and analysis systems and make it possible to monitor disease progression using only a small amount of sample from the patient.

0.3V Biopotential Sensor Interface for Stress Monitoring

7.07

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

Sponsorship: Delta Electronics

Miniaturized sensor nodes have a very tight power budget, especially in the case of implantables and health monitoring devices that require long operation lifetimes. Designing sensor nodes with such a low power budget is a challenging problem, which requires careful design in both analog blocks and back-end digital signal processing blocks. In the present AFE solutions, theoretically more power can be saved at lower supply levels, but this comes at the cost of losing dynamic range, speed, and robustness. In order to further reduce the supply without significantly compromising these performance metrics, the analog architectures used in the signal acquisition need to be re-designed.

The motivation of this work is to explore the limits of low-voltage design by using simplistic, yet robust circuit topologies. We present a 0.3V biopotential sensor interface (amplifier+ADC) that achieves state-of-the-art power efficiency and ensures enough circuit reliability with reduced dynamic range requirement. The AFE has large-signal cancellation ability in order to suppress the effect of unexpected motion-artifact signals coming from the environment and the sensor interface. The system will be used to measure facial electromyographic (EMG) signals from patients in order to provide diagnostic information about temporomandibular joint disorder (TMJD), migraines and some orthodontic problems.

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Low Power Processor for Real-Time Video Motion Magnification

7.08

P. Raina, A. P. Chandrakasan

Sponsorship: Intel

There are a number of phenomena around us that exhibit small motions that are invisible to the naked eye. Recent research in computer vision has shown that computational amplification can be used to reveal such motions. These motion magnification algorithms use video as input and analyze each pixel for slight variations over time and amplify the variation. This technology can be used for various applications such as non-invasive health monitoring, industrial infrastructure monitoring, and structural integrity assessment, which currently rely on more expensive hardware and human intervention.

However, state of the art motion magnification algorithms are computationally intensive and achieve a throughput of only 0.23 frames/second while consuming 10.36 uJ/pixel energy on mobile CPUs at 1080p resolution. This energy consumption is 4 orders of magnitude higher than what is required for efficient implementation on battery operated mobile devices.

In this work, we propose to design a low power processor to accelerate motion magnification achieving real-time performance on 1080p video at 30 frames/second, while consuming only ~10nJ/pixel. We propose to use the following techniques to achieve this: 1. Separable filtering with reordering in laplacian pyramid computation to reduce the number of multiplies by 5.25x and number of adds by 3x, and zero-skipping to reduce pyramid buffering size by 23.3%. 2. Compression of the computed laplacian pyramid data to reduce memory bandwidth and save system energy. 3. Detecting active pixels, which are typically < 50% of total pixels, from the temporal filter output to reduce computation and memory bandwidth and performing dynamic voltage and frequency scaling while keeping the throughput constant to reduce energy. These techniques enable efficient integration of this motion magnification technology into portable devices.

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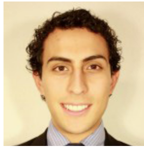
Point-of-Care Microfluidic Electronic Detection of Protein Biomarkers

7.09

D. Wu, D. Rios-Aguirre, J. Voldman

Sponsorship: Analog Devices, Inc.



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Research Interests: BioMEMS, electronic devices, electronics, medical devices & systems, MEMS & NEMS, microfluidic devices & systems, sensors.

Measuring protein biomarkers in blood are of significant clinical importance and have a fast growing market. However, traditional blood tests are performed in centralized laboratories and may take days to deliver results to patients. The need of large blood sample volumes (~mL) also makes it challenging to perform testing of newborns and preemies who have limited blood. We are developing a magnetic bead-based microfluidic electronic biosensor which provides precise and immediate results at the Point-of-Care and requires small blood volumes (uL), potentially allowing for safer and faster blood testing of neonates.

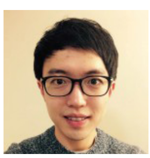
To prepare the blood test, magnetic microbeads conjugated with antibodies and enzymes are added to the sample. The biomarkers in the sample will bind to the antibodies due to specific antigen-antibody interactions. The magnetic beads are then transported to the sensor through microfluidic channels and attach to the immobilized antibodies on the electrode's surface. The conjugated enzymes on the microbeads catalyze a chemical reaction and generate current which is measured by the electronic sensor. The amount of protein in the original sample is proportional to the measured current. Previous results performing this biochemical immunoassay to measure Human IL-6 (~22 kDa) indicate that the sensitivity of our sensor is ~1pg/mL, which is sensitive enough to measure most of the protein biomarkers in blood.

The electronic sensor is a portable, Point-of-Care, low noise device, with a precision down to 500 pA that is capable of measuring 5 electrodes simultaneously, making it possible to perform parallel measurements of multiple proteins, which would make the blood tests more precise. The benefits of multiplexing include cost and time reductions, redundancy, and reliability in the measurement.

Non-invasive Central Arterial Pressure Waveform Monitoring using Ultrasound

7.10

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



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

An arterial blood pressure (ABP) waveform provides valuable information in diagnosing and treating cardiovascular diseases of patients in an intensive-care unit. The ABP waveform is usually obtained through a pressure transducer connected to an arterial catheter. Although considered a gold standard, the disadvantage of this method is its invasive nature. 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 because of the potential portability of an ultrasound system and its non-invasive nature, thus minimizing patient 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 obtaining a flow-area plot during a cardiac cycle and then 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 streaming data to the PC at above 10Mbps using an USB interface. A clinical test conducted on nine healthy subjects demonstrates the feasibility of this technique. Currently, the prototype device is re-designed to overcome identified limitations of the device from the previous experiment, such as measurement sensitivity to position and orientation of the transducer assembly.

3D Chaotic Printing: Using Simple Chaotic Flows to Fabricate Complex Microstructures

7.11

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Sponsorship: MIT-Tecnológico de Monterrey Nanotechnology Program, CONACyT, Fundación México en Harvard

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Research Interests: Biological devices & systems, biomaterials.

Chaos has the ability to create complex and predictable structures. We demonstrate the use of simple chaotic flows for the fabrication of complex 3D microstructures in cross-linkable or curable liquids using a process that we refer to as 3D chaotic printing. We inject a drop of ink (i.e., a drop of a miscible liquid, fluorescent beads, or cells) into a viscous Newtonian liquid and then apply a chaotic mixing recipe. This generates a complex structure in just a few flow applications. This structure is then preserved with high fidelity and reproducibility by rapid crosslinking or curing of the material. The 3D structure is the result of the rapid alignment of the injected material to the flow manifold. Therefore, its main features are reproducible and the overall process of fabrication is quite robust. Moreover, since the process is deterministic, it is amenable to computational modeling using Computational Fluid Dynamics (CFD).

In 3D chaotic printing, the interface between the injected material and the fluid matrix grows exponentially with time, and the volume of the injection is finite. Consequently, the average thickness of the lamellae of the material rapidly decreases from a scale of millimeters (the diameter of the injected drop) to one of nanometers. This exponentially fast increase in the interface, as well as the accompanying rapid decrease in the relevant length scales of the microstructure (which still preserves high resolution), is not currently achievable by any other 3D printing technique.

We illustrate potential applications for this technology, including the rational reinforcement of constructs by the chaotic alignment of cells and nanoparticles, the fabrication of cell-laden fibers, the development of highly complex multi-lamellar and multi-cellular tissue-like structures for biomedical applications, and the fabrication of bioinspired catalytic surfaces.

A Gold-Based Stretchable Multielectrode Array for Muscle Stimulation and Recording During Peripheral Nerve Repair

7.12

K. Vyas, M. McAvoy, O. Khan, J. Tsosie, R. Langer, D. Anderson
Sponsorship: Department of Defense

Traumatic muscle injuries that involve peripheral nerve damage require over a year for repair. Denervated muscles undergo atrophy, which affects functional recovery. The objective of this research is to fill the need for a biocompatible interface that can stimulate denervated muscle and also monitor nerve regeneration. The central hypothesis is that this device will reduce muscle denervation/atrophy and in effect, promote functional recovery. A 1 mm^2 prototype device was built on a silicon wafer as the fabrication platform. The design consists of embedding an array of gold-based microelectrodes within a thin substrate of polyimide elastopolymer. The device is connected to an Arduino which outputs the electrical stimulation.

Initial biocompatibility of our device was evaluated against a control device via implantation in Lewis rats for 30 days. The tissue around the devices was measured and they both cumulated 30.00 um +/- 5.00 fibrotic tissue. In vivo implantations were performed on Lewis rats to test stimulating and recording capabilities. The Arduino outputted a square pulse wave to the device and stimulated the gastrocnemius muscle. Visible contractions can be seen with an amplitude as low as 20 mV. The muscle activity is recorded on a continuous feed using MATLAB. Wireless functionality of the device can be implemented to remove transcutaneous wires. The parameters for therapeutic stimulation need to be fine-tuned through long-term testing for optimal regeneration in the future.

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Communications, integrated circuits, systems.

Dual Frequency Combs Based 220-to-320GHz Spectrometer in 65nm CMOS for Gas Sensing

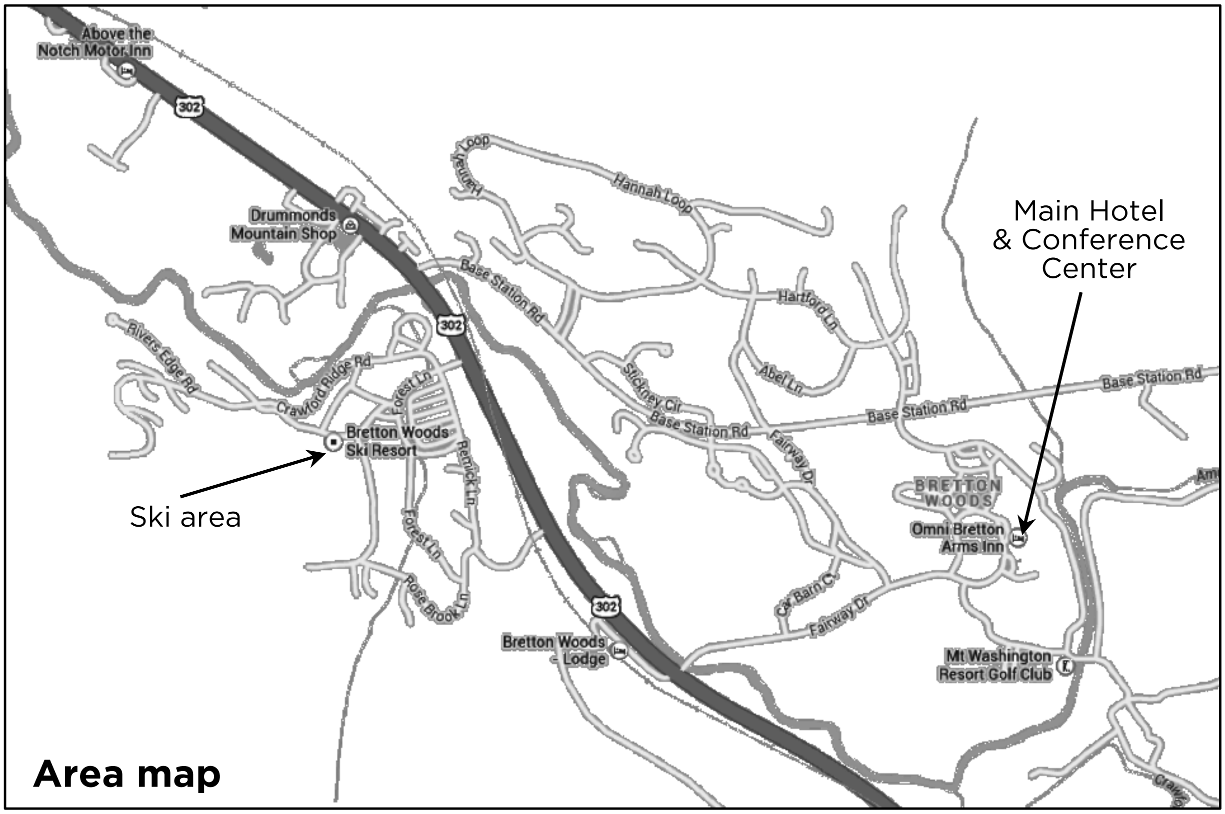
7.13

C. Wang, R. Han

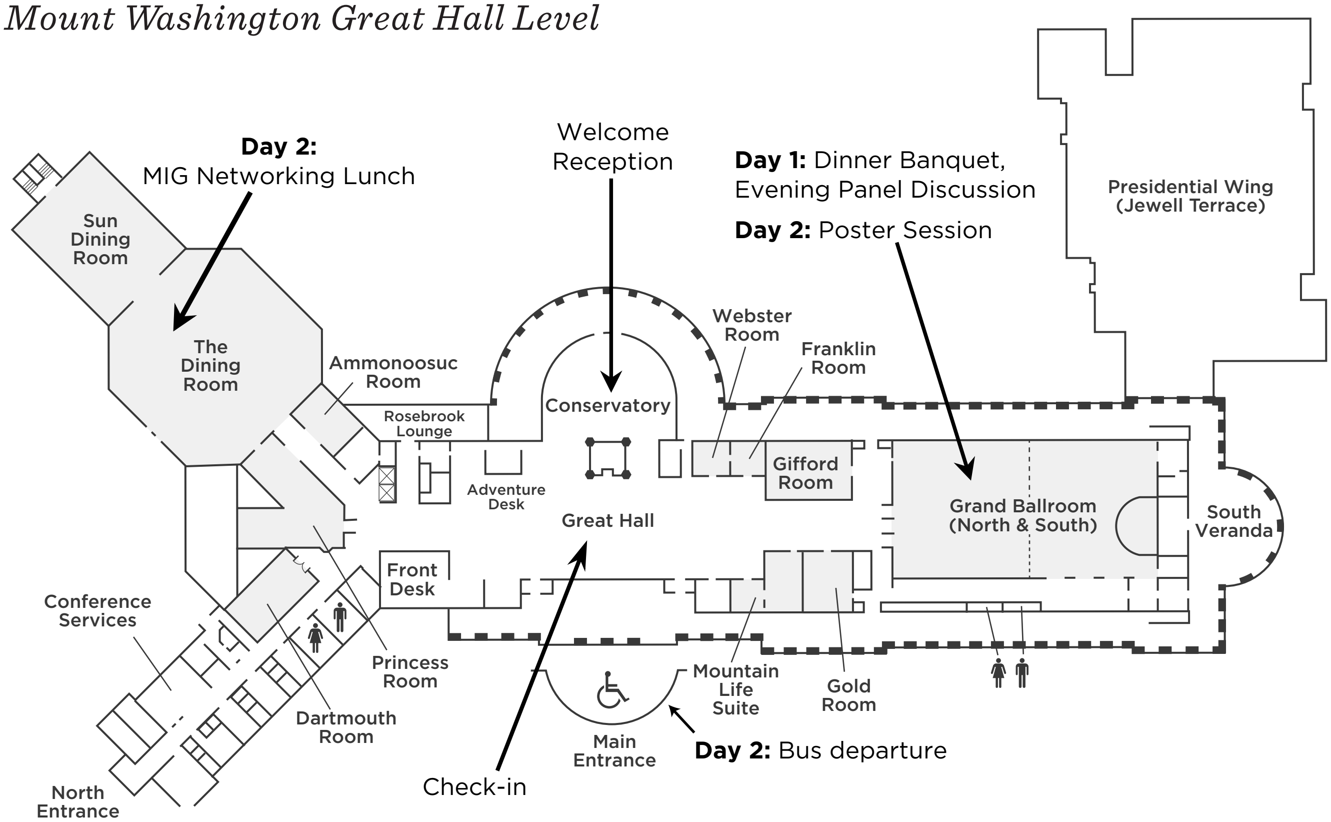
Millimeter-wave/terahertz rotational spectroscopy offers ultra-wide-detection range of gas molecules for chemical and biomedical sensing. Therefore, wideband, energy-efficient, and fast-scanning CMOS spectrometers are in demand. Spectrometers using narrow-pulse sources and electromagnetic scattering are broadband, but their resolutions do not meet the requirement (10kHz) of the absolute specificity. Alternatively, a scheme using a single tunable tone does not only exhibit significant trade-off between bandwidth and performance, but also suffers from molecular saturation, which sets an upper limit for the strength of incident electrical field. Therefore, traditionally, given a typical 10kHz resolution and 1ms integration time, scanning a 100GHz bandwidth with a single tone takes as long as 3 hours.

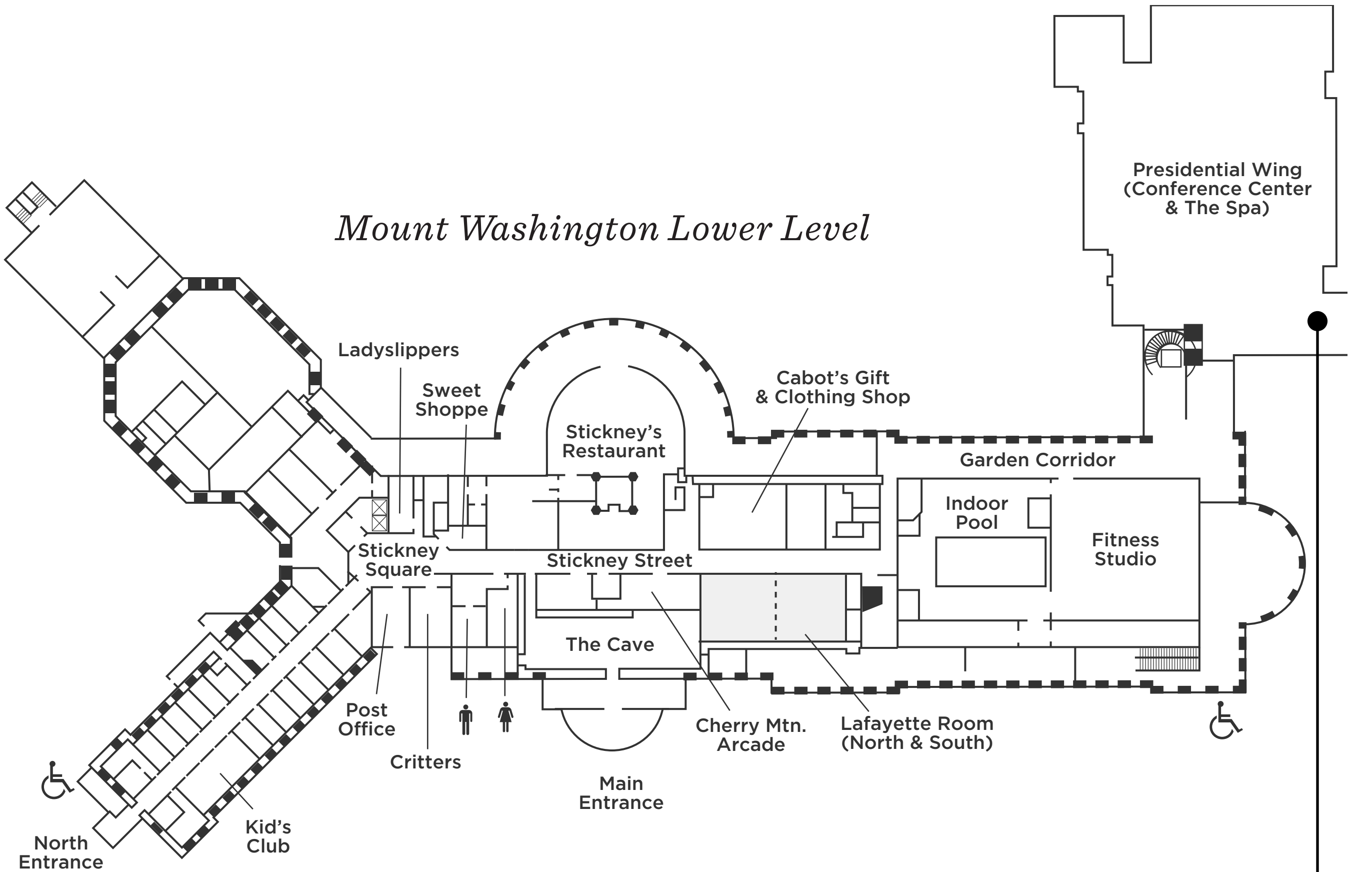
This paper reports a rapid, energy-efficient spectrometer architecture based on dual-frequency-comb scanning. A 220-to-320GHz CMOS spectrometer prototype based on this architecture is demonstrated with a total measured radiated power of 5.2mW and a NF of 14.6 to ~19.5dB. Through distributing the electromagnetic energy over 20 comb lines and performing bi-directional parallel operation, this spectrometer realizes 20 times faster scanning speed. A fraction of rotational absorption spectrum of acetonitrile (CH_3CN) is measured with linewidth of 380 kHz, which demonstrates the absolute specificity of the spectrometer.

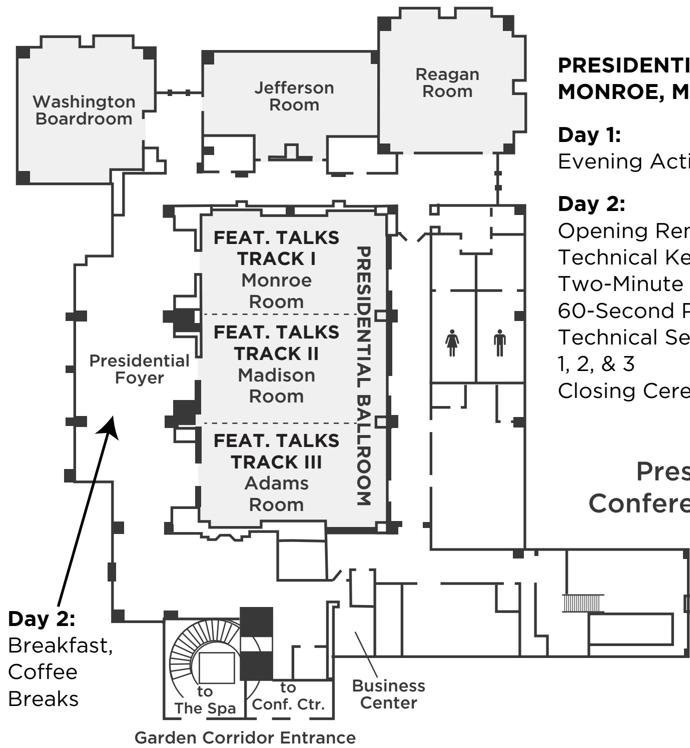
MAPS



Mount Washington Great Hall Level







PRESIDENTIAL BALLROOM/ MONROE, MADISON, ADAMS ROOMS

Day 1:
Evening Activities

Day 2:
Opening Remarks
Technical Keynote
Two-Minute MIG Pitch
60-Second Poster Pitches
Technical Sessions
1, 2, & 3
Closing Ceremonies

Presidential Wing Conference Center Level

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IN APPRECIATION OF OUR MICROSYSTEMS INDUSTRIAL GROUP MEMBER COMPANIES:

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DSM
Edwards Vacuum
Foxconn Electronics
HARTING
Hitachi High-Technologies
Intel

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Lam Research Co.
NEC
Qualcomm
Samsung
STMicroelectronics
TSMC
Texas Instruments