Microsystems Technology Laboratories

The mission of MIT's Microsystems Technology Laboratories (MTL) is to foster world-class research, education, and innovation at the nanoscale. MTL's activities include integrated circuits, systems, electronic and photonic devices, MEMS (microelectromechanical systems), bio-MEMS (biomedical microelectromechanical systems), molecular devices, nanotechnology, sensors and actuators, and many other applications. MTL's research program is largely interdisciplinary.

Since October 2013, MTL has been led by Professor Jesus del Alamo. A recent addition to MTL's 50 core faculty is Professor Ruonan Han, a new hire in the Department of Electrical Engineering and Computer Science.

MTL maintains service facilities providing campus-wide access to advanced micro- and nanofabrication capabilities as well as access to sophisticated Computer-Aided Design (CAD) software infrastructure and tools. During the reporting period, MTL had 396 users of the fabrication facilities and 240 CAD tool users (61 users took advantage of both services). These users represent 26 MIT departments, labs, and centers and 136 faculty research groups.

In October 2014, MTL celebrated its 30th anniversary. More than 300 people from a wide variety of institutions attended a two-day event, which included a banquet and symposium. The event constituted both a look back at MTL's past and a look forward to the bright prospects for nanotechnology and nanosystems at MIT with the coming of MIT.nano.

Figure 1. Professor Paul Penfield addresses the panel on nanosystems during MTL's 30th anniversary symposium. Photo: David Sella.

In October 2014, MIT established a formal relationship with Tecnológico de Monterrey, one of the largest universities in Latin America, to bring students and faculty from Mexico to Cambridge for fellowships, internships, and research stays in MIT labs and centers. The agreement initially focuses on research at the frontier of nanoscience and nanotechnology, and will be managed by MTL. As part of this program, MTL hosted 24 students, postdocs, and faculty this year in three separate one-week sessions as part of the MTL nanoLab hands-on course on nanotechnology.

Figure 2. (Left to right): Eduardo Medina Mora, Mexico's ambassador to the United States; Tecnológico de Monterrey President Salvador Alva; MIT President L. Rafael Reif; and José Antonio Fernandez Carbajal, the chairman of the board of trustees at Tecnológico de Monterrey. Photo: Dominick Reuter.

MTL engages users in a number of technical events. In both fall and spring of each academic year, the laboratory hosts a seminar series spanning diverse technical areas. The seminars, which are open to the public, are organized by a committee chaired by Professor Tomas Palacios. In addition to these regular seminars, MTL hosts one doctoral dissertation seminar each semester featuring a recent MTL PhD graduate, as well as occasional distinguished and executive seminars featuring a VIP from one of MTL's member companies. In September 2014, MTL hosted the visit of Dr. David Hemker, Senior Vice President and Chief Technology Officer at Lam Research Corporation.

Each January, MTL holds the Microsystems Annual Research Conference (MARC) run by MTL graduate students. The 2015 MARC was co-chaired by students Shireen Warnock (from Professor del Alamo's group) and Marek Hempel (from Professor Palacios's group). MARC is broadly attended by industry, faculty, students, and staff, as it provides a unique opportunity to learn about research in the diverse areas encompassed by MTL, while fostering interactions among the MTL community. The 2015 event was held on January 22 at the Boston Marriott in Quincy, MA, attracting more than 200 students, postdocs, faculty, staff, and industry partners, representing six MIT departments and 14 Microsystems Industrial Group member companies.

Figure 3. Group photo taken at MARC2015. Photo: Paul McGrath/MTL.

Administrative Updates

Facilities

During the past year, MTL continued to replace aging tools, extended the usefulness of existing tools, and acquired new capabilities. A Greenflo energy efficient hood, donated by Reynolds Tech, was installed to replace acid-hood2. Two Annealsys Rapid Thermal Annealers, acquired last year for silicon and III-V semiconductors, were also installed to replace very old systems. Other installation projects started the prior year were also completed. A 2D-material transfer hood was set up in the Exploratory Materials Laboratory (EML) fume hood to relieve the use by MTL members of a hood in a private faculty lab. Using funds from the Department of Materials Science and Engineering and MTL, an Atomic layer deposition for EML, to be used on wide range of substrate materials, was acquired at a significant discount. With MTL funds, a Critical Point Dryer was also acquired at a discount. Finally, with support provided by the Vice President of Research Replacement Fund, a new e-beam evaporator for EML was ordered to replace the one inherited from the defunct Microlab, which dated to 1989. With these new tools, we are able to support new programs and strategic initiatives (e.g., atomic layer etching).

In addition to equipment renewal, MTL improved its management systems. For example, a new bar chart has been developed to monitor tool uptime and utilization using data collection and graphing from CORAL. To speed up new user introduction to the lab, key milestones in the registration and training processes were identified, thereby allowing staff to track the progress of new users and to identify bottlenecks.

In order to make better decisions regarding fabrication tool and clean room space utilization, a new MTL Equipment Acquisition Committee was set up. Professor Nicholas Fang of Mechanical Engineering chairs this committee, which includes faculty and postdocs from six departments.

Industry Interactions

MTL partners with industry through the Microsystems Industrial Group (MIG) consortium. The companies that are members of MIG support MTL research and operations through a membership fee and, in some cases, by providing access to state-of-the-art semiconductor fabrication design tools and processes. MIG member companies donate major pieces of equipment to MTL and provide access to their integrated circuit chip fabrication services. Members of the MIG's Industrial Advisory Board provide significant guidance in shaping the vision of MTL.

During AY2015, Edwards Vacuum joined the Microsystems Industrial Group. Edwards is a leading developer and manufacturer of sophisticated vacuum products, abatement systems, and related services. As part of the launch of the Edwards Vacuum membership, an MTL group led by Professor del Alamo visited two Edwards locations in the United Kingdom. One of the first engagements of Edwards with MTL was the extended visit of engineer Anthony Taylor to the group of Dr. Luis Velasquez-Garcia in MTL.

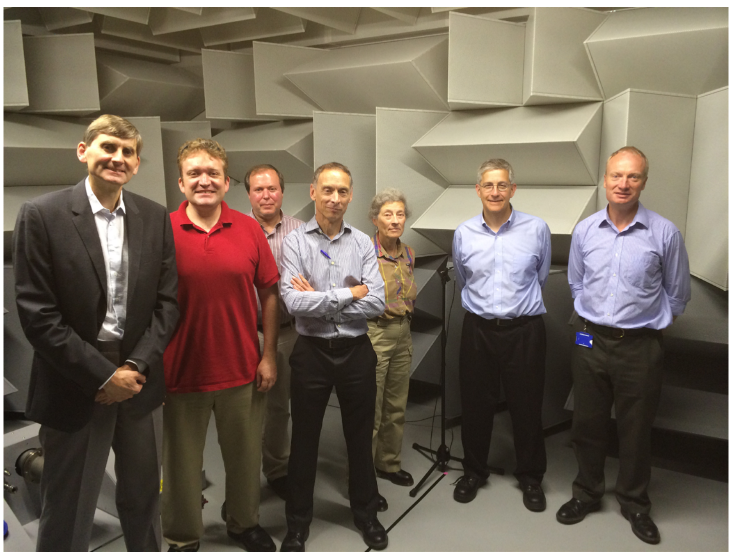


Figure 4. From left to right: Jesus del Alamo (MTL), Luis Velasquez-Garcia (MTL), Anthony Taylor (Edwards), Fred Underwood (Edwards), Vicky Diadiuk (MTL), Bill Holber (MTL), and Nigel Schofield (Edwards) at Edwards anechoic chamber in Burgess Hill, UK, where the sound characteristics of Edwards Vacuum products are studied.

MTL hosted its annual Industrial Advisory Board meeting on Friday, January 23, 2015, with all 15 MIG member companies in attendance. Representatives from the various companies included: Chorn-Ping Chang, Adam Brand, and Davis Lee (Applied Materials); Susan Feindt (Analog Devices); Anthony Keen and Mike Wilders (Edwards Vacuum); Yihui Qui, Jeng Feng Lee, and Matt Mai (Foxconn); Yuki Kikuchi (Hitachi High Technologies); Ghavam Shahidi (IBM); Scott List (Intel); Nerissa Draeger (Lam Research Corporation); Brian Brandt and Brett Miwa (Maxim Integrated Products); Hidenori Shimawaki (NEC Corporation); David Hansquine (Qualcomm); Dennis Buss and Heather McCulloh (Texas Instruments); Doug Chen-Hua Yu (Taiwan Semiconductor Manufacturing Company); and Marco De Fazio (STMicroelectronics).

Professor del Alamo began the meeting with the "Director's Update." Professor Vladimir Bulovic provided an update on MIT.nano and the MIT Innovation Initiative. Other faculty speakers included Gang Chen, Ruonan Han, Jing Kong, and Jongyoon Han. Vicky Diadiuk and Duane Boning gave updates on the MTL facilities and CAD/Information Technology services, respectively.

Four centers affiliated with MTL provide the opportunity for MTL member companies and other companies to become engaged in focused research initiatives. These were the Center for Integrated Circuits and Systems, the MIT GaN Energy Initiative, the Medical Electronic Device Realization Center, and the MIT-MTL Center for Graphene Devices and 2D Systems.

One of the unique benefits that member companies receive is the opportunity to have a scientist or engineer participate in the research activities of an MTL-affiliated faculty member or research center. This past year there have been 12 visitors from MTL member companies:

James Fiorenza (Analog Devices [ADI]): with Professor Palacios

Tom O'Dwyer (ADI): with Professor Charles Sodini

Anthony Taylor (Edwards Vacuum): with Professor Velasquez

Yihui Qiu (Hon Hai Precision Industry Co., Ltd., trading as Foxconn Technology Group): with Professor Anantha Chandrakasan

Jeng-Feng Lee (Foxconn): with Professor Chandrakasan

Yuki Kikuchi (Hitachi High Technologies): with Professor Scott Manalis

Cheng-Wei Cheng (IBM): with Dr. Diadiuk

Brian Brandt (Maxim Integrated): with Professors Sodini and Joel Voldman

Seung Jun Bae (Samsung): with Professor Hae-Seung Lee

Marco De Fazio (STMicroelectronics): with Professor Palacios

Dennis Buss (Texas Instruments [TI]): with MTL

Ginger Wang (Taiwan Semiconductor Manufacturing Company Limited [TSMC]): with Professor Sodini

Examples of interactions with MTL's industry partners include the following visits to member companies by MTL faculty and students:

July 2: Harry Lee at TSMC (Hsinchu, Taiwan)

July 3: Jesus del Alamo at TSMC (Leuven, Belgium)

August 5–6: Jesus del Alamo, Luis Velasquez, Vicky Diadiuk and Bill Holber at Edwards Vacuum (United Kingdom)

August 19, 20: Anantha Chandrakasan at TI (Dallas, TX)

August 21: Dirk Englund and Ruonan Han at Intel (Portland, OR)

September 8: Tomas Palacios at Analog Devices (Wilmington, DE)

October13: Charles Sodini at TI

October 15: Duane Boning at TSMC

October 24: Tomas Palacios at TI (Dallas) and Lam Research (San Jose, CA)

November13: Tomas Palacios at Intel

November 14: David Perreault at Samsung

December 3: Jesus del Alamo at TSMC

December 4: Jesus del Alamo at Foxconn (Taipei, Taiwan)

December 5: Vivienne Sze at Samsung (Richardson, TX)

December 8: Jesus del Alamo at Samsung (Dongtan, China)

January 15: Group of nine faculty members from MTL visited Qualcomm Research Center (San Diego, CA)

January 27: Ruonan Han at Analog Devices

January 27: Dimitri Antoniadis at TSMC

February 6: Vivienne Sze at Qualcomm Research Center

February 24: Jesus del Alamo at Lam Research

March 5: Jesus del Alamo and Bill Holber at Applied Materials (Gloucester, MA)

March 5: Charles Sodini at TSMC

March 24: Vivienne Sze at Qualcomm (Austin, TX)

Visits to MTL by member companies during the past academic year include:

July 21: The Industrial Liaison Program hosted a Qualcomm visit to MIT

August 6: Toshiyuki Ikeda, President of Hitachi High Technologies

September 18: Intel recruiting visit to MIT

September 18: Lam Research Corporation recruiting at MIT

September 19: Lam Research Day at MIT

October 2: Joseph Steigerwald from Intel in Portland, OR, gave a presentation

October 3: Intel recruiting at MIT

October 10: Carlos Diaz from TSMC Hsinchu visited MTL

October 14: Group from Samsung visited Dave Perreault

October 22: Roawen Chen from Qualcomm presented at an MTL seminar

October 23–24: Rob Gilmore from Qualcomm visited MIT

October 31: Hidenori Shimawaki and Shinishi Yoruzu from NEC Corporation visited with the MTL faculty

January 20: Jets Chang, Kaje Chan, and Chihcheng Lai visited from Foxconn

February 3: Intel recruiting visit to MIT

February 19: Nevine Nassif from Intel gave a presentation on processor design

March 11: Heike Riel from IBM Research in Zurich presented at an MTL seminar

March 17: Jeffrey Marks from Lam Research visited various MTL faculty members

March 18: Sam Fuller from Analog Devices presented at the MTL Spring Seminar Series

March 31: Visit from Vincent Roche, Analog Devices president and CEO

April 1: Joe McPherson from Texas Instruments presented at an MTL seminar

April 28–30: TSMC Day at MTL

June 16: Charles Hsu, Emerging Business Opportunities (Foxconn) hosted a luncheon with ILP

Outreach and Educational Activities

In support of MTL's mission to provide access to advanced fabrication technologies, MTL makes its facilities available to industry users through the Fabrication Facilities Access (FFA) program and to users from academia and government agencies through the Outreach Program. In the period of reporting, MTL supported the activities of five different companies, including an MIT startup.

MTL supports MIT's educational mission through three courses held at the laboratory: 6.152J Micro/Nano Processing Technology, which introduces the theory and technology of micro/nano fabrication, 3.042 Materials Project Laboratory, which provides student project teams the capabilities to design and fabricate a working prototype using materials processing technologies, and 6.07J Projects in Microscale Engineering, which is a project-based introduction to manipulating and characterizing cells and biological molecules using microfabricated tools for the life sciences.

MTL also supports two Department of Electrical Engineering and Computer Science (EECS) initiatives: the Women's Technology Program and the Super Undergraduate Research Opportunities Program (SuperUROP), as described below.

Women's Technology Program

The Women's Technology Program (WTP) was created in 2002 to encourage young women with strong math, science, and analytical abilities to pursue studies in engineering and computer science. The program provides women with positive female role models, college-level computing and engineering experience, and an understanding of what engineers and scientists do and how they work.

Participants in WTP have an opportunity during the summer for a hands-on experience in the microfabrication facilities of MTL. As a fun and engaging exercise, small groups go through the fabrication steps needed to transfer a group photograph onto a silicon wafer. Each student receives a wafer that displays the image of the group. Feedback from students has been very positive, and the "picture wafers" are a great reminder of their summer at MIT.

SuperUROP

SuperUROP, initiated by EECS in fall 2012, engages students in a yearlong research experience in which they participate in the course "Preparation for Undergraduate Research." SuperUROP promotes direct interaction with faculty and industry sponsors, cultivates student creativity and professional development, and encourages students to consider the ethical and entrepreneurial aspects of their work. In AY2015, 17 students in the program worked in the Microsystems Technology Laboratory.

MTL has been proud to partner with EECS in the SuperUROP program, providing $3,000 of subsidized access for each student whose project makes use of MTL computational or fabrication facilities. Recently this subsidy has been extended to all undergraduate students at MIT.

Research Highlights

Dina El-Damak, Anantha P. Chandrakasan
Solar Energy Harvesting for Ultra-low Power IoT Devices

This work presents a solar energy harvesting system with integrated battery management and startup using 3.2 nW of quiescent power. The chip can use a solar cell to charge a battery as well as directly power an electronic device with a regulated voltage rail, and it can power the device directly from the battery while using a single inductor. The system can operate with input power of 10 nW to 1 μW with a peak efficiency above 80%, while previously published power converters that target similar input power and voltage ranges had efficiencies around 40% to 50%. To achieve this performance, the control circuit in this work is designed in an asynchronous fashion that scales the effective switching frequency of the converter with the level of the power transferred. The on-time of the converter switches adapts dynamically to the input and output voltages for peak-current control and zero-current switching. For input power of 500 nW, the proposed system achieves an efficiency of 82%, including the control circuit overhead, while charging a battery at 3 V from 0.5 V input. In buck mode, it achieves a peak efficiency of 87% and maintains efficiency greater than 80% for output power of 50 nW-1 μW with input voltage of 3 V and output voltage of 1 V.

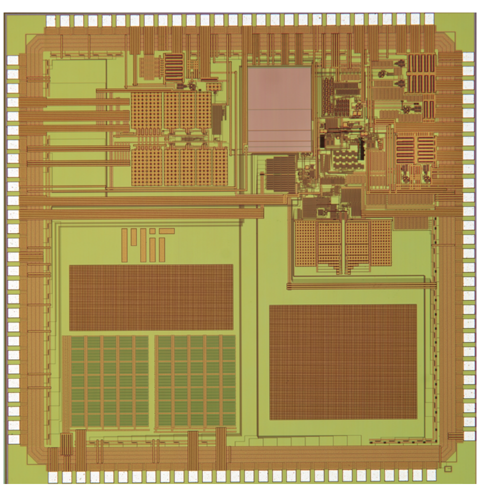


Figure 5. Solar energy harvesting chip micrograph.

Eric S. Winokur, Tom O'Dwyer and Charles G. Sodini
A Low-Power, Dual-Wavelength Photoplethysmogram SoC with Static and Time-Varying Interferer Removal

A low-power, reflectance-mode, dual-wavelength Photoplethysmogram (PPG) System-on-Chip was fabricated in a 0.18 μm 1P6M CMOS process. Architectural changes to remove up to 100 μA of static interferers without compromising the bandwidth of the system and attenuate time-varying interferers by 87dB in a low-power manner were shown. Tight digital integration allowed for duty cycle optimization, which led to a nominal power consumption of only 425 μW. The duty cycle was determined by the number of photons required for an SNR (signal-to-noise ratio) of 30, given a worst case pulsatile to static PPG ratio of 0.25%. The chip was designed such that the photon shot noise of the photodiode dominated the overall noise. These results were demonstrated experimentally in the chip shown.

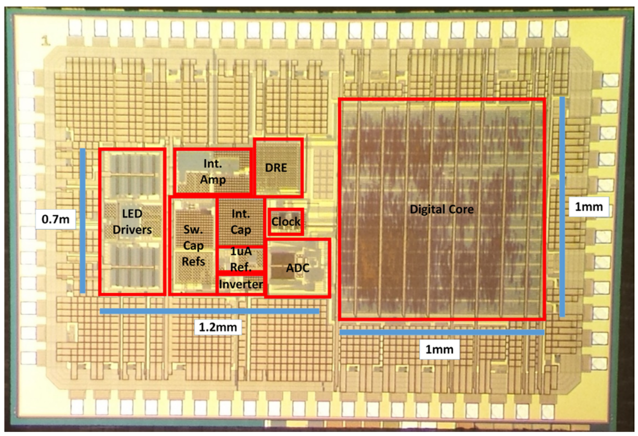


Figure 6. Photomicrograph of the PPG SoC with major circuit blocks labeled.

Jesus A. del Alamo
Self-Aligned InGaAs Quantum-Well Metal-Oxide-Semiconductor Field-Effect Transistors

The increasing difficulty of Si to support the historical rate of progress of CMOS scaling known as Moore's Law has prompted the search for alternative channel materials with enhanced transport characteristics. Among possible candidates, InGaAs has recently emerged as a leading contender for n-channel MOSFETs. This is because of its outstanding electron transport characteristics. Our group is investigating transistor architectures to exploit the unique properties of InGaAs. We have innovated a self-aligned process that is entirely based on Si-compatible materials and processes and that has resulted in the most compact and highest performing scaled transistor demonstrations in the literature.

We have recently carried out a detailed vertical and lateral scaling study of InGaAs Quantum-Well MOSFETs. We have found that this planar transistor design is at the limit of scaling at around a gate length of 50 nm. This is an important result because it strongly suggests that further scaling requires three-dimensional device architectures, such as the FinFET, Trigate MOSFET, or Vertical Nanowire MOSFET.

While unable to scale to the smallest desired dimensions, our InGaAs MOSFETs represent an excellent platform to study the physics of relevance to future nanoscale InGaAs transistors. In the last year, we have carried out an experimental study in transistors with a very tight layout that for the first time shows the role of band-to-band tunneling (BTBT) and gate-induced drain leakage in the off-state characteristics of these devices. We show how a parasitic floating-body bipolar transistor that naturally is created inside the MOSFET results in BTBT current amplification that can be as high as 1,000-fold. This is a significant concern because it prevents effective transistor turn-off. Furthermore, this large contribution to off-state current should also be present in 3D device designs. In our study, we suggest a number of strategies to mitigate this problem.

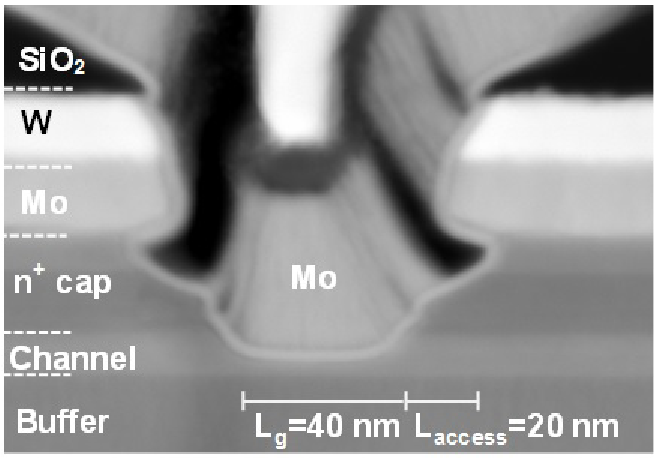


Figure 7. Cross-section of self-aligned quantum-well InGaAs MOSFET.

Jongyoon Han
Using Electrokinetic Flow to Strengthen Tooth Enamel

Professor Jongyoon Han's group research focuses on molecular and cell separation and sorting technologies, as well as the novel use of various types of ion-selective membranes.

As reported in a recent publication (Gan et al., *Journal of Dental Research*, 94(5) 615-621, 2015), Professor Han and the Micro/Nanofluidic BioMEMS Group is introducing a new method that enables infiltration of therapeutic molecules (dental resins) deep into human tooth enamel, which is the hardest tissue found, characterized by 2–5 nm-sized nanopores. Infiltration of various molecules and fluid into the enamel could serve various applications such as enamel restoration and teeth whitening, but previous methods of infiltration were limited to only about ~50 μm of infiltration depth. The team, led by Professor Han and his dentist collaborator (Dr. Frederico de Sousa, Federal University of Paraiba, Brazil), reports that one can achieve a deep infiltration (a few millimeters—the entire depth of tooth enamel) of dental resin into human enamel by invoking electrokinetic flow via a small DC voltage. Unlike pressure-driven flow, an electrokinetic flow mechanism has the unique feature that its flow velocity is not dependent on the pore size, therefore enabling appreciable flow even through the narrowest nanopores of tooth enamel. The publication prompted a discussion with Colgate Inc. for a potential research collaboration, which is currently being planned.

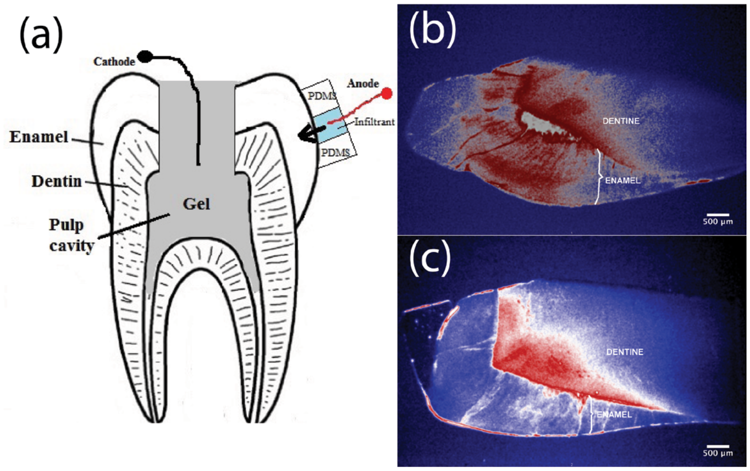
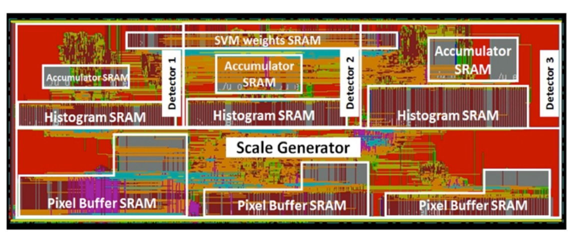


Figure 8. (a) Drawing describing the experimental set up of the whole tooth experiment. The dentin and enamel layers above the pulp chamber were mechanically removed. The cavity formed from the floor of the pulp chamber to the outer enamel layer was filled with a gel where a platinum wire (cathode) was inserted. At the opposite side of the pulp chamber, a PDMS device was adhered to the tooth with a central reservoir containing the infiltrant material (KCl solution or resin) and another platinum wire (anode), so that the flow direction was from the tooth surface to the pulp chamber (arrow). Drawings (b) and (c) show typical fluorescence microscopy images of the tooth crown's ground sections of infiltrated (b) and non-infiltrated (c) surfaces. In actual in vivo implementation, the cathode (e.g. micro-needle) can be inserted directly into the gum tissue without the removal of dental tissues.

Vivienne Sze
Energy-Efficient Real-time Object Detection

Working towards developing energy-efficient architectures and algorithms for real-time object detection for embedded sensing applications (e.g. UAV, security, smartphones), we designed a low-power, real-time high definition (1,920 x 1,080 @ 60 fps) object detection chip using HOG features that can detect multiple object sizes with only 45 mW of power (0.3 nJ/pixel) in a 45 nm Silicon on insulator (SOI) process. The design supports 12 different object scales, and performs detection on the gradient images, which reduces energy cost 40% and area cost by 2.4x of the scale generation without sacrificing detection accuracy.

Area	2.80x0.96 mm^2
Max Frequency	270 MHz
Scales/frame	12
Gate count	490 kgates
On-chip SRAM	0.538 Mbit



Snapshot of layout

Figure 9. Layout and specs of energy-efficient real-time object detection processor.

Jeffrey H. Lang
Nano-Electromechanical Switches

A team of graduate students and postdocs, under the supervision of Professors Vladimir Bulovic, Timothy Swager, and Jeffrey Lang, are developing a NanoElectroMechanical switch that operates with an organic molecular monolayer between its contacts. A schematic of a two-terminal switch, labeled following the functionality of a MOSFET, and with its gate and drain connected for experimental simplicity, is shown in Figure 10. In a three-terminal switch the gate is recessed. Closing the switch is effected with electrostatic gate-source actuation typically below 1 V. When closed, the switch conducts from drain to source via tunneling through the molecular monolayer; when open, its conduction reduces by a factor of 10^6 or more. The importance of the molecular monolayer is that it prevents contact sticking, thereby eliminating a major roadblock to using the switch for digital logic and RF switching. Current work focuses on reducing the actuation voltage and improving fabrication yield.

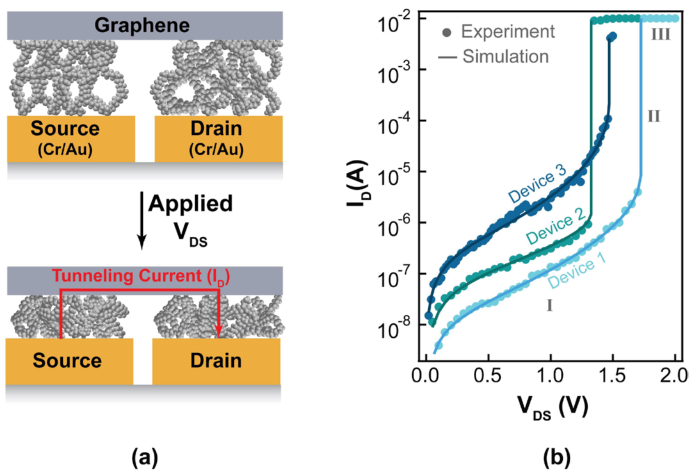


Figure 10. (a) A two-terminal switch fabricated with interdigitated Au bottom electrodes, self-assembled PEG-dithiol molecular layer and transferred CVD graphene top electrode. A drain-source voltage (VDS) is applied to decrease the molecular gap and modulate the tunneling current (ID). (b) Current-voltage characteristics for three experimental switches of the design shown in (a) fitted to the theoretically simulated behavior.

P. J. Ponce de Leon, F. A. Hill, E. V. Heubel, and L. F. Velasquez-García
Parallel Nanomanufacturing via Electrohydrodynamic Jetting from Microfabricated Externally-Fed Emitter Arrays

Electrohydrodynamic jetting can create high-quality nano-thick films at lower temperature than standard semiconductor processing. A key advantage of electrospinning (electrohydrodynamic jetting of nanofibers) over other nanofiber generation methods is its versatility in producing fibers of arbitrary length that can be metal, ceramic, or semiconducting. The applications of electrospun nanofibers include tissue scaffolds, electrodes, and separation membranes.

We created a technology for high-throughput generation of polymer nanofibers using planar arrays of microfabricated, externally fed electrospinning emitters. The devices deposit uniform arrays of imprints comprising fibers with diameters on the order of a few hundred nanometers using solutions of dissolved polyethylene oxide in water and ethanol as working fluid. We measured mass flux rates four times higher than the reported production rate of leading commercial free-surface electrospinning sources. Throughput increases with increasing array size at constant emitter density, showing that the design can be scaled up with no loss of productivity.

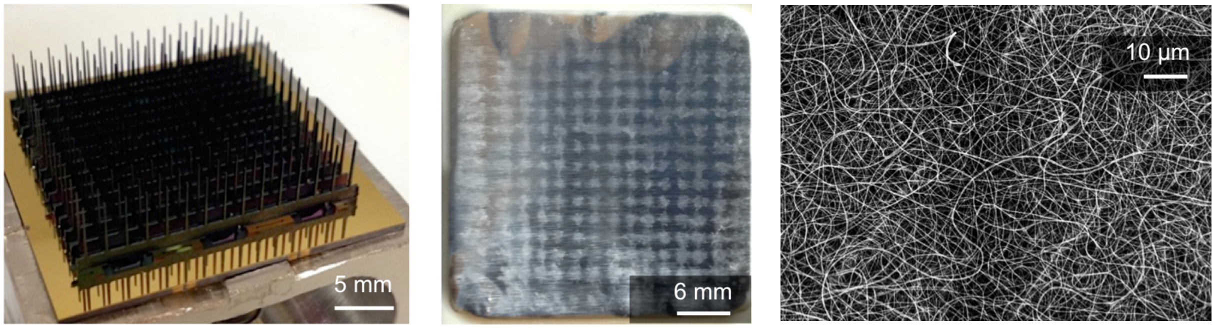


Figure 11. (a) an array of 15×15 externally fed electrospinning emitters (25 emitters/cm2); (b) collector imprints from an array of 225 emitters (25 emitters/cm2); (c) close-up of an imprint evidencing the nanofiber structure.

Tomas Palacios, Lili Yu, Ahmad Zubair, Xu Zhang, Yuxuan Lin, Yuhao Zhang
CMOS-based Electronics with Two-Dimensional Semiconductors

Due to their extraordinary structural and electrical properties, two-dimensional (2D) materials are currently being pursued for applications such as thin-film transistors and integrated circuits. One of the main challenges that still needs to be overcome for these applications is the fabrication of complementary metal oxide semiconductor (CMOS) circuits. In this work, we experimentally demonstrate the first high-performance, air-stable CMOS technology on 2D materials—WSe_2 in our case. These circuits show almost ideal voltage transfer characteristics, full logic swing, and high noise margin with different supply voltages. More importantly, logic gates such as inverters show large voltage gain (~38) and small static power (pico-watts), paving the way for low-power electronic systems in 2D materials.

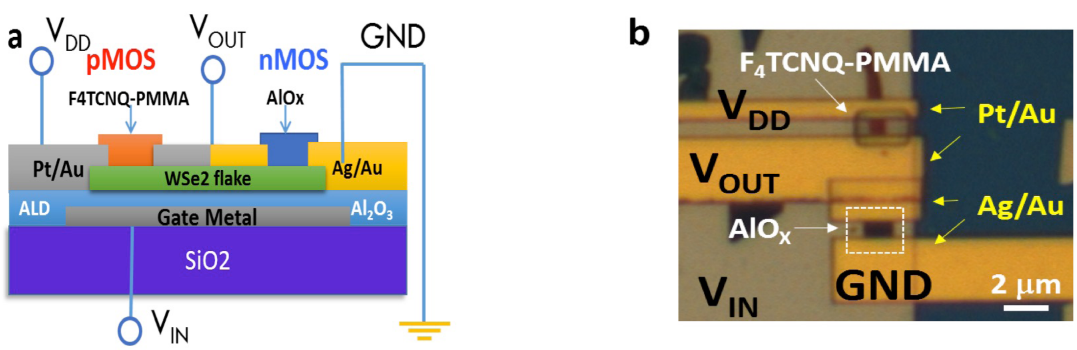


Figure 12. a) Cross-section of the WSe2-based CMOS technology developed by the Palacios team at MTL. b) Optical micrograph of the fabricated logic gate.

Polina Anikeeva
Optoelectronic Neural Probes and Scaffolds

In the past year, the work in Bioelectronics Group has developed a palette of fiber-based optoelectronic probes that enabled, for the first time, simultaneous neural recording, optical stimulation, and drug delivery in the brain of freely moving mice. Our flexible probes based on polymers, composites, and low melting temperature metals evoked minimal foreign body response, allowing for probes to maintain their functions for months. In fact, certain devices maintain their functionality after more than a year after implantation. This indicates that our approach may provide a path towards reliable, multifunctional neural interfaces essential for the development of future neural prosthesis. In addition to neural probes, we have applied fiber fabrication methods to the development of optoelectronic neural scaffolds. We found that hollow fiber-based scaffolds can be engineered to support and direct nerve growth. The latter may find future applications in repair of peripheral nerve injuries.

Figure 13. A macroscopic template of a fiber capable of transmitting electrical signal, light and drugs is pulled to create brain probes with a diameter <50 µm. Canales et al. demonstrate the utility of the probes for studying neural function in freely moving animals for extended periods of time in the March 2015 issue of Nature Biotechnology.

Ruonan Han
High-Power, Phase-Locked THz Radiation from Silicon Integrated Circuits

Integrated circuits operating in the terahertz range are critical to the next-generation microsystems for communication and sensing. However, THz radiation is extremely difficult to generate from room-temperature integrated circuits, especially using silicon. To overcome the technical barriers due to the excessive loss and inferior speed of silicon transistors, Professor Han proposed a device-electromagnetism co-design approach, which efficiently consolidates nonlinear device optimization, sub-THz oscillation, and harmonic generation into a multi-mode, compact radiator structure. A 130-nm BiCMOS array prototype achieves the highest radiated power (3.3 mW @ 320 GHz) and DC-to-THz radiation efficiency (0.54%) so far among all THz integrated radiators It also demonstrates the first THz phase-locked loop for on-chip radiation, which is essential for coherent THz imaging, spectroscopy and tera-scale communications with high-order modulation. Lastly, the chip integrates 16 radiators within only 0.8 mm^2 area—the radiator density is four times higher than the prior arts. This work is a collaboration with Cornell University and STMicroelectronics.

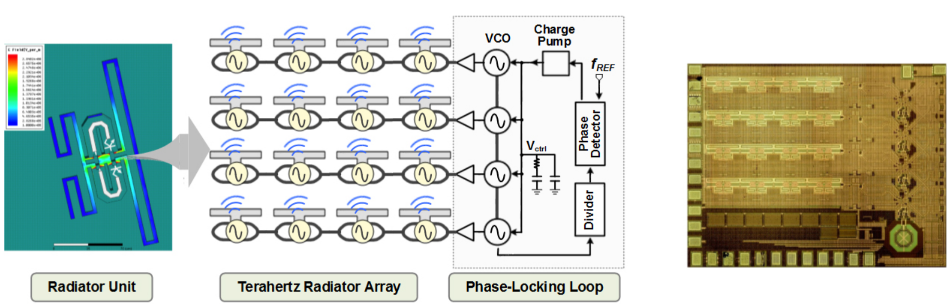


Figure 14. (left) An array of high-power SiGe THz radiators with integrated phase-locked loop. (right) The micrograph of the chip. The area of the radiator array is only 0.8 mm^2.

Professor Karl Berggren
Three-dimensional Nanofabrication Using Hydrogen Silsesquioxane/poly(methylmethacrylate) Bilayer Resists

Three-dimensional (3D) devices are difficult to fabricate, but offer unique advantages over planar devices for many applications. There has been a growing interest in 3D devices such as photonic crystals and metamaterials, and nanoelectromechanical systems. However, methods for generating 3D devices are generally slow and expensive. Therefore, a simple and rapid fabrication process for complex 3D nanostructures is necessary. In this work, we developed two self-aligned processes for fabricating 3D nanostructures using a hydrogen silsesquioxane (HSQ) and poly(methylmethacrylate) (PMMA) bilayer resist stack, which allow more arbitrary patterns compared to existing approaches. We used the difference in dose sensitivity between HSQ and PMMA to pattern the resist stack in a single electron-beam writing step without removing the wafer. The resulting 3D nanostructures naturally achieved vertical self-alignment without the need for any intermediate alignment between layers. Self-aligned mushroom-shaped posts and freestanding supported structures were demonstrated.

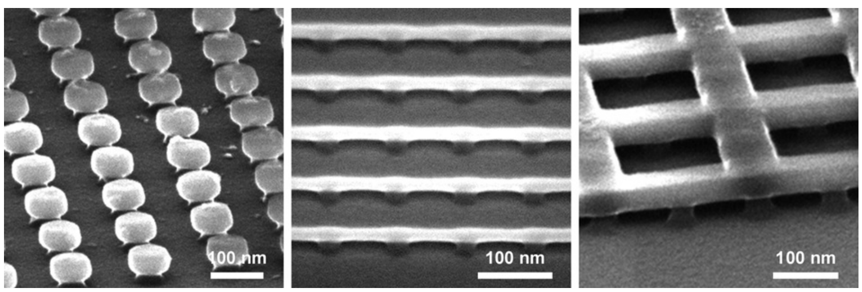


Figure 15. SEM images of 3D nanostructures fabricated from the newly developed process. Mushroom-shaped posts with well-defined top disks over lower posts (left). Freestanding linear top layer structures with a lower layer post support (middle). Freestanding cross grid structures with a lower layer post support (right).

Professor Scott Manalis
Device Can Measures Distribution of Particles in a Microfluidic Channel

A new technique invented at MIT can measure the relative positions of tiny particles as they flow through a fluidic channel, potentially offering an easy way to monitor the assembly of nanoparticles, or to study how mass is distributed within a cell. With further advancements, this technology has the potential to resolve the shape of objects in flow as small as viruses, the researchers say. The new technique, described in the May 12 issue of *Nature Communications*, uses a device first developed by MIT's Scott Manalis and colleagues in 2007. That device, known as a suspended microchannel resonator, measures particles' masses as they flow through a narrow channel.

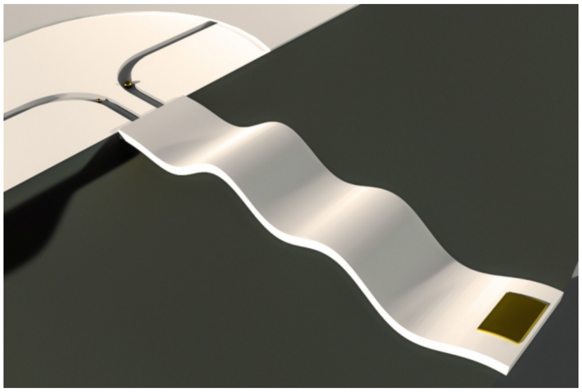


Figure 16. A suspended microchannel resonator measures particles' masses as they flow through a narrow channel. The original mass sensor consists of a fluid-filled microchannel etched in a tiny silicon cantilever that vibrates inside a vacuum cavity. As cells or particles flow through the channel, one at a time, their mass slightly alters the cantilever's vibration frequency. This illustration depicts a snapshot of a cantilever vibrating at its first four resonant modes.

Awards and Honors

An MIT team at the intersection of microelectronics and synthetic biology won a $100,000 Qualcomm Innovation Fellowship for their proposal "BacMOS: Electronic biosensors using synthetic biological transducers." The team consisted of PhD students Phillip Nadeau (EECS/MTL) and Mark Mimee (Microbiology), with their advisors, Anantha Chandrakasan and Timothy K. Lu (July 2014).

Figure 17. Mark Mimee and Phillip Nadeau.

Professor Harry Lee received the 2014 Committed to Caring Award, given by the Office of the Dean for Graduate Education at MIT (August 2014).

Sameer Joglekar, PhD candidate with Professor Palacios, received the Best Poster Award at the International Workshop on Nitride Semiconductors (IWN) held in Wroclaw, Poland. The work that Joglekar presented was selected from more than 500 presentations at IWN, the top conference in the field (August 2014).

Figure 18. Professor Lee helps weave the academic community together by fostering scholarship and mentoring students.

Professor Palacios received the Young Scientist Best Presentation Award from the Japan Society of Applied Physics (September 2014).

Professor Antoniadis received the 2014 Aristotle Award, given by the Semiconductor Research Corporation (SRC) to recognize SRC-supported faculty whose deep commitment to the educational experience of students has had a profound and continuing impact on their professional performance (September 2014).

Figure 19. The presentation of the 2014 Aristotle Award to Dimitri Antoniadis (center) by Larry Sumney (left), SRC President and CEO, at TECHCON 2014. Also appearing in the photo is Steven Hillenius, executive vice-president at Semiconductor Research Corporation.

The paper by M. Tikekar, C.-T. Huang, V. Sze, and A. P. Chandrakasan, "Energy and Area-Efficient Hardware Implementation of HEVC Inverse Transform and Dequantization," presented at the Institute of Electrical and Electronics Engineers (IEEE) International Conference on Image Processing in October 2014, was selected as "Top 10% Paper Award" (October 2014).

Professor Palacios received the distinction of Fellow of the Frontiers of Engineering Program of the National Academy of Engineering (November 2014).

Professor Anikeeva received the Engineering in Medicine and Biology Society of the IEEE Brain Grand Challenges Young Investigator Award (November 2014).

Professor Han was selected for the "Emanuel E. Landsman (1958) Career Development Chair" (November 2014).

MTL graduate student Wenjie Lu received first prize for the 2014 Ernst Guillemin Award for Best Master's Thesis in Electrical Engineering by the Department of Electrical Engineering and Computer Science. His thesis was titled "Nano-scale Ohmic Contacts for III-V MOSFETs" and was supervised by Professor del Alamo (November 2014).

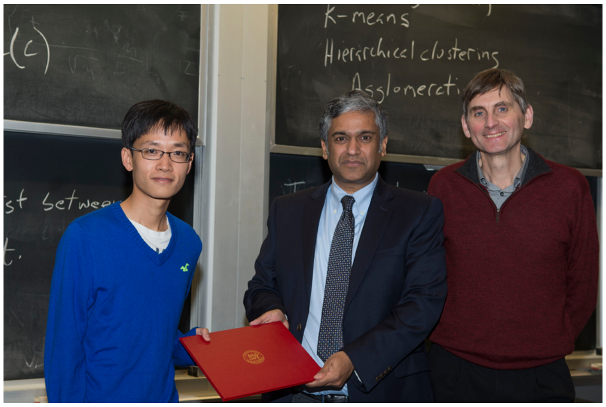


Figure 20: EECS Department Head Professor Chandrakasan presents Wenjie Lu with the first place 2014 Ernst Guillemin Master's Thesis Award. His advisor, Professor del Alamo, is on the right. Photo: Patsy Sampson.

Professor Antoniadis received the 2015 IEEE Jun-ichi Nishizawa Medal from the Federation of Electric Power Companies for contributions to metal oxide semiconductor field-effect transistor physics, technology, and modeling (December 2014).

Professor del Alamo was named a fellow of the American Physical Society for fundamental contributions to the development of III-V compound semiconductor electronics (December 2014).

A paper by F. A. Hill, E. V. Heubel, P. Ponce de Leon, and L. F. Velasquez-Garcia on "High-Throughput Ionic Liquid Ion Sources Using Arrays of Microfabricated Electrospray Emitters with Integrated Extractor Grid and Carbon Nanotube Flow Control Structures" was selected as one of the three JMEMS RightNow Papers of the October 2014 issue of the IEEE *Journal of Microelectromechanical Systems* (December 2014).

Professor Sze, core member of the Microsystems Technology Laboratories, received a 2014 Defense Advanced Research Projects Agency (DARPA) Young Faculty Award (December 2014).

Figure 21. Vivienne Sze, left, received the award from Dr. Fariba Farhoo, DARPA Young Faculty Award program manager, on October 3, 2014, in Arlington, VA.

An MIT paper co-authored in 2008 by then postdoctoral fellow Dae-Hyun Kim and Professor del Alamo was selected among the top ten most influential papers presented at the International Electron Devices Meeting in the last decade. The paper was titled "30 nm E-Mode InAs PHEMTs for THz and Future Logic Applications" (December 2014).

Dr. Amir Tavakkoli K.G. received the Best Postdoc Presentation Award from the Materials Research Society Symposium Directed Self Assembly for Nanopatterning. He is advised by Professor Karl Berggren (December 2014).

PhD candidate Allen Hsu received the 2014 MTL Doctoral Dissertation Seminar Award at MIT in December 2014. His research is supervised by Professor Palacios.

PhD student Jianqiang (Jerome) Lin received the 2014 Roger A. Haken Best Student Paper Award for his presentation on "Novel Intrinsic and Extrinsic Engineering for High-Performance High-Density Self-Aligned InGaAs MOSFETs: Precise Channel Thickness Control and Sub-40 nm Metal Contacts" at the 2014 International Electron Devices Meeting. Co-authors of the paper are his co-advisors, Professors Antoniadis and del Alamo (December 2014).

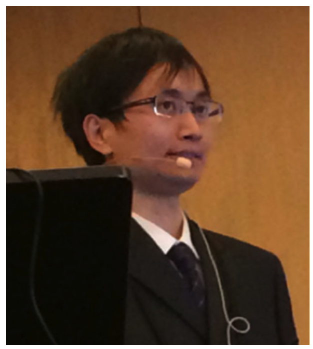


Figure 22. PhD student Jianqiang (Jerome) Lin at the 2014 International Electron Devices Meeting.

PhD candidate Yu-Hsin Chen received the 2015 Analog Devices Outstanding Student Designer Award. His PhD advisor is Professor Sze (January 2015).

Anantha Chandrakasan, Karen K. Gleason, L. Rafael Reif, and alumnus Dr. Ghavam Shahidi were elected to the National Academy of Engineering (NAE). Election to the NAE is among the highest professional distinctions accorded to American engineers. Academy membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature," and to the "pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education" (February 2015).

Undergraduate student Christina Tringides was awarded a Fulbright Fellowship. She also received the Outstanding Senior Thesis Award from the Department of Materials Science and Engineering. She is advised by Professor Anikeeva (April 2015).

Graduate student Sam Nicaise and postdoctoral associate Richard Hobbs received the MIT Infinite Mile award (April 2015).

Zheng Zhang and Jianqiang Lin, two students from MTL-affiliated research groups, were granted the 2014 National Award for Outstanding Self-financed Students Abroad (April 2015).

Figure 23. From left to right: Zheng Zhang, Consul General Qiyue Zhang, Professor Luca Daniel, and Jianqiang Lin.

PhD student Alex Guo was granted the MIT Graduate Women of Excellence Award, 2015. Guo's research is supervised by Professor del Alamo (April 2015).

PhD candidate Dan Congreve was selected for the Spring 2015 MTL Doctoral Dissertation Seminar in May 2015. His research is supervised by Professor Marc Baldo (May 2015).

Figures 24 and 25. Dean of MIT's School of Engineering Ian Waitz with Debroah Hodges-Pabon and with Patricia Burkhart. Photos: Paul McGrath.

Patricia Burkhart and Debroah Hodges-Pabon were recipients of the MIT School of Engineering's 2015 Infinite Mile Award (May 2015).

Research Assistant Alyssa Cartwright received the Morais ('86) and Rosenblum ('86) UROP Award. This award is given at the annual EECS Celebration in recognition of the best undergraduate research project in EECS. Alyssa's advisor is Professor Berggren (May 2015).

Professor Palacios received the Ruth and Joel Spira Teaching Award from the Department of Electrical Engineering and Computer Science (May 2015).

PhD candidate Amr Suleiman received third place in the 2015 Broadcom Foundation University Research Competition for his project "A 45mW Object Detector Accelerator for High Definition Video at 60fps." He is supervised by Professor Sze (June 2015).

Professor Charles Sodini received an honorary fellowship award from Hong Kong University of Science and Technology (June 2015).

Figure 26. Professor Sodini and President of Hong Kong University of Science and Technology.

A paper by S. Cheng, F. A Hill, E. V. Heubel, and L. F. Velasquez Garcia on "Low-Bremsstrahlung X-Ray Source Using a Low-Voltage High-Current-Density Nanostructured Field Emission Cathode and a Transmission Anode for Markerless Soft Tissue Imaging" was selected as one of the three JMEMS RightNow Papers of the April 2015 issue of the *IEEE Journal of Microelectromechanical Systems* (June 2015).

Jesús A. del Alamo
Director
Donner Professor of Electrical Engineering