Microsystems Technology Laboratories

The mission of the Microsystems Technology Laboratories (MTL) is to foster world-class research, education, and innovation at the nanoscale and micro scale. Science and technology supported by MTL can help solve some of the world's greatest problems in resources (energy, water, and frequency bands, for example), information and communications, health, security, and transportation, to name a few. Researchers all over MIT have been engineering new materials, structures, devices, circuits, and systems using MTL's facilities and services in search of new solutions and applications. Most of MTL's research programs are highly interdisciplinary and encompass integrated circuits, systems, communication technologies, machine learning (ML), electronic and photonic devices, microelectromechanical systems (MEMS), biomedical MEMS (bio-MEMS), molecular devices, medical devices, nanotechnology, sensors, and actuators.

Currently, our core faculty comprises 58 members representing seven departments across the Schools of Engineering and Science. While our faculty members are principally drawn from the Departments of Electrical Engineering and Computer Science (EECS), Mechanical Engineering, and Materials Science and Engineering (DMSE), we continue to see expanding interest and engagement from faculty in the Departments of Biological Engineering, Chemical Engineering, Chemistry, and Physics. In addition, because circuits, sensors, and devices are integral to a virtually unlimited range of applications, we have built and continue to strengthen collaborations and interactions with many other research labs and centers across the Institute, including the Research Laboratory of Electronics (RLE), the MIT Energy Initiative, the Institute for Medical Engineering and Sciences (IMES), the Materials Processing Center, the Materials Research Laboratory (MRL), the Computer Science and Artificial Intelligence Laboratory, the Koch Institute for Integrative Cancer Research, and the Institute for Soldier Nanotechnology. MTL core faculty serve MIT and the global community in significant leadership positions across the Institute. We are honored to note that MTL's core faculty includes MIT president Rafael Reif, Provost Martin Schmidt, School of Engineering (SoE) dean Anantha Chandrakasan, Department of Mechanical Engineering head Evelyn Wang, Associate Mechanical Engineering Department Head for Education Rohit Karnik, MIT.nano inaugural director Vladimir Bulović, Faculty Head of Electrical Engineering Joel Voldman, RLE director Marc Baldo, and MRL co-director Carl Thompson.

Since its inception, MTL has managed a set of shared experimental facilities in Buildings 39 and 24 that currently host more than 150 fabrication and analytical tools and serve a community of about 400 students and postdocs from all corners of MIT. When the new MIT.nano building was completed, the administrative management of these fabrication facilities was transferred to MIT.nano at the end of FY2019. The physical transfer of the fabrication environment, equipment, and tools into Building 12 is in progress. During the transitional period, the fabrication capabilities in Building 39—including diffusion, lithography, deposition, etching, and packaging—continue to be available to the entire MIT community and outside researchers.

MTL manages an information technology (IT) infrastructure that supports state-of-the-art computer-aided design (CAD) tools for device, circuit, and system design and serves a community of more than 200 students and postdocs from all over MIT. This includes providing access to some of the most advanced commercial integrated circuit fabrication processes available in the world today through strong MTL relationships with major semiconductor manufacturers. MTL also supports network infrastructure and about 350 desktop and server machines for MTL resident students, staff, and faculty. In combination with the 361 unique MTL fabrication users (in addition to users from cooperating government research laboratories, domestic and international universities, and fabrication facilities access companies), 502 distinct MIT students and postdocs from 27 different departments, laboratories, and centers carried out their research in MTL's facilities or used its design services over the past year.

Integration of MTL and RLE

Goals

As described in the 2020 president's report, MTL and RLE began the integration of the two laboratories in the summer of 2020. The integration was based on the recommendation of a committee formed by Joel Voldman, Electrical Engineering associate department head, in late May 2019. The committee was overwhelmingly positive about the integration provided that MTL's identity, community, culture, activities, and strong interaction with industry, as well as the Institute's support of MTL, could be maintained. The committee identified many benefits to be gained by the integration. For example, MTL will gain a much larger research footprint by tapping into RLE's large array of research areas. Also, companies that are members of MTL's Microsystems Industrial Group (MIG) will have access to a much broader range of research conducted within the integrated structure, and in return MTL will bring to the RLE community expertise in community and culture building and industry interactions.

Since early March 2020, RLE director Baldo and MTL director Harry Lee have met weekly to design an action plan for the committee's recommendation. It has been proposed that MTL and RLE be progressively integrated to better serve the objectives of the process within our communities.

Efficient delivery of research administration services is best funded by allocation so that precious discretionary resources can be preserved. The appropriate scale for an allocation unit performing experimental work is approximately $50 million per year, corresponding to at least 50 active principal investigators (PIs). RLE is a good example of a robust allocation unit with a long tradition of successful delivery of administrative services.

However, vibrant intellectual communities such as MTL require a focus that is impossible to achieve in such a large allocation unit. The historical success of MTL demonstrates the communal focus provided by a central discretionary resource maintained by the community and reinvested within the community.

The integration of the two laboratories was pursued with the following goals:

- Expand the MTL intellectual community and maintain the distinct MTL identity
- Provide more diversified and robust financial resources, including improved support for faculty startup packages

- Remove legacy barriers between MTL and RLE (e.g., transfer of space to the combined RLE/MTL entity)
- Transition MTL administration from MIG support to the RLE allocation model
- Continue the CAD/computing services that MTL has provided to the broader MTL community for decades
- Harness synergy between MTL and the new quantum consortium in the RLE Center for Quantum Engineering

Integration Process

In order to ensure a smooth transition, two advisory committees were formed. The first, the Faculty Advisory Committee, oversees matters associated with the intellectual integration, MIG, branding, and the merging of complementary yet distinct cultures. Administrative matters of concern to faculty and staff are brought to the second committee, the Administrative Advisory Committee, for consideration and implementation as needed.

The Faculty Advisory Committee members are Professors Harry Lee (co-chair), Marc Baldo (co-chair), Jeff Shapiro, Will Oliver, and Duane Boning. The issues considered by the committee include the following:

- Importance of maintaining a strong relationship with SoE
- How will future MTL directors be appointed? Will SoE have a voice?
- Will the MTL director be an associate director of RLE?
- How will startup packages be coordinated? Will the Electrical Engineering faculty chair coordinate with RLE/MTL directors? In return, can the MTL director's Extended Engineering Council seat be maintained?
- Need for the continuation of Institute support of MTL to be negotiated given MTL's financial support of MIT.nano

The Administrative Advisory Committee includes a comprehensive group of administrative stakeholders representing key business functions leading all aspects of the administrative integration. The committee is led by Richard Petruzzelli, assistant director for administration, in partnership with lab directors Harry Lee and Marc Baldo and Stacy McDaid, the MTL administrative officer. The group formed on May 28, 2020, agreeing to provide professional expertise within its professional domain. The committee's diverse functional expertise drives the administrative integration forward over time.

The Administrative Advisory Committee members are as follows:

- SoE: Michelle Coyne (director of human resources), Catherine Kim (assistant dean for human resources and administration), Elizabeth Lennox (assistant dean for finance and administration), John Maher and Mary Ellen Sinkus (administrative officers)

- MTL: Stacy McDaid (administrative officer)
- RLE: Dave Foss (assistant director), Cindy Matheson (senior fiscal officer), Richard Petruzzelli (assistant director), Melissa Sheehan (manager of fiscal administration), Rachel Drake (human resource manager)
- Office of the Vice President for Research: Ron Hasseltine (assistant provost for research administration), Lynn Hinds (manager for finance and research administration), Kristen Shikes (manager of human resources and administration)

Integration Timeline

There are two determinants of the timeline for the integration.

Maintenance of the MTL Research Culture and Industrial Consortium

MTL is a long-standing intellectual community organized around an industrial consortium (MIG). Prior assessments of the potential integration between RLE and MTL have emphasized that it is crucial to maintain the distinct culture and links to industry that MTL has fostered. Indeed, from the perspective of RLE, one of the key benefits of the integration is the model that MTL provides for vibrant intellectual communities under a broader RLE service umbrella. In particular, RLE has created a consortium to focus the burgeoning quantum science and engineering community that can synergize with the MTL MIG.

Consequently, there is strong consensus that a gradual integration will yield the most benefit to MTL and RLE principal investigators. This will allow MTL PIs to readily benefit from RLE's robust service infrastructure, avoid disruption in MTL's distinct intellectual community, and ensure that PIs are able to pursue their research agenda seamlessly. There will be a deliberate effort to integrate the cultures and ensure robust support for PIs as they transition their administrative activities to RLE. We will also simultaneously sustain the professional engagement and productivity of RLE headquarters staff to support engagement with MTL activities.

Shift to the Allocation Model for Services

A central goal of the integration of RLE and MTL is to shift the support of administrative services in MTL away from discretionary funds sourced from MIG. The combination of RLE's service model and MTL's existing industrial consortium creates an opportunity to achieve efficiencies. The allocation model in RLE scales with research volume and preserves discretionary funds for startup packages and infrastructure investments.

Thus, the financial integration of RLE and MTL will be determined by the conversion of MTL research to allocation. Existing MTL contracts have not been budgeted for allocation, and their administration must be supported by MIG funds. To affect the transition to the allocation model, it is necessary to budget new proposals with allocation.

In summary, financial integration of research contracts will continue for at least the next three years. New allocation income is expected to ultimately support approximately three full-time-equivalent positions, with one new position reaching financial viability each year, starting in 2022. To maintain existing MTL contracts, it will be necessary to support an administrative staff in MTL outside the allocation model (i.e., with MIG and Institute support) until at least January 2024.

Integrating Operations and Setting Priorities

A three-year phased multistep process was implemented in summer 2020 that includes a series of sequential initiatives identified for execution on a quarterly basis. Depending on the complexity, some activities may be completed within the quarter to which they are assigned. Once started, other activities may roll over to future quarters as needed to bring them to completion. Each activity is focused on key functional areas, as described below.

Transitioning MTL Pre-Award (Year One)

Given the lag between funding and proposal submission, it is inevitable that we must support the preparation of allocated proposals for MTL PIs before there is allocation income to support the expertise in RLE pre-award.

The pre-award capability in RLE is deep, with the entire financial team experienced in preparing proposals. Nevertheless, the total MTL pre-award activity represents a 20% to 25% increase over the current RLE pre-award volume. Given the unpredictable nature of pre-award demand and the associated workflow volume, we started a triaged proposal request process in year one. Stacy McDaid, Richard Petruzzelli, and Cindy Matheson (RLE pre-award lead) determined whether RLE staff, MTL staff, or a combination will would handle a specific proposal. This approach allowed us to ensure a reasonable workload for staff and to simultaneously execute the highest level of service to PIs. At the end of June 2020, we implemented the RLE request for proposals as a pre-award request and communication tool for all MTL PIs. Doing so enhanced communication between PIs and administrative staff and facilitated the assessment and triage process for MTL proposal requests (as discussed above). RLE has since engaged with many MTL PIs for proposals prepared and submitted by RLE during the past year.

Transitioning MTL Post-Award (Year Two)

We have commenced the transition of MTL PIs to RLE, with initial efforts focused on the significant and complex portfolio of Professor Max Shulaker. In July 2020, Professor Shulaker was fully integrated into RLE with respect to all functional areas, including pre-award, post-award, and human resources (HR) functions. Melissa Sheehan is Shulaker's fiscal officer; the RLE fiscal team handles all pre-award activities, and the RLE HR team handles Shulaker's HR activity. Following his successful transfer, we intend to transfer MTL PIs with priority given to junior faculty.

During the transition, activities in MTL headquarters must be maintained. MTL capabilities have been supplemented with the addition of Kristin Cook, MTL's new fiscal officer. We anticipate that Kristin will fully transition to RLE toward the end of the integration.

IT Operations (Year Three)

Both RLE and MTL presently support IT teams, with MTL also supporting a CAD service on behalf of the Institute. It would not be possible to support the MTL CAD user facility under allocation. RLE can, however, manage the CAD user facility and collect user fees on its behalf. Depending on the revenue obtained, it may be necessary for MTL to continue to subsidize the facility. RLE prioritizes discretionary spending on startup packages and renovations and will not use the returns from the endowment to subsidize the CAD facility.

General IT support can be funded through allocation. During the integration process, we will carefully evaluate the demand in the combined RLE and MTL for general IT support. Because of the timeline of the expected allocation income, even if we decide to expand our general IT support, there will be no possibility of expanding RLE headquarters until January 2022 at the earliest.

Administrative Operations (MTL-RLE Fit-Gap Analysis)

During the transition, it is essential that we monitor the performance of our combined activities to prevent services lapses for RLE and MTL PIs. This task is the responsibility of the Administrative Advisory Committee.

MTL's administrative staff, including the headquarters staff, faculty administrative assistants, and the computing staff, will stay in the current MTL space during and after the completion of the integration.

Human Resources (Years One and Two)

After the full integration, the MTL and RLE HR functions will be combined and paid from allocation.

Additional Functions

Both RLE and MTL conduct important operations in terms of facilities, communications and outreach, major programs, events, and support and management of administrative assistants. Planning for each of these functions, together with planning for the future faculty leadership structure of the combined RLE-MTL organization, has been guided by the Administrative Advisory Committee and faculty committees.

Maintaining and growing MIG is vital for the RLE-MTL integration from financial and cultural perspectives. It requires strong community participation, and thus maintaining the sense of community is critical. We anticipate that current MTL activities such as the Microsystems Annual Research Conference (MARC), the MTL Seminar Series, student social hours, Microsystems Mini Technical Symposia, and publication of the Microsystems Annual Research Report and quarterly newsletters will continue beyond the integration. With the integration, these activities will expand beyond the current MTL constituents. For these reasons, the current administrative support needs to be maintained continuously during and after the transition.

Industry Engagement

Microsystems Industrial Group

MTL partners with industry through the Microsystems Industrial Group consortium. The MIG member companies support MTL research and operations through a membership fee. Members of MIG's Industrial Advisory Board (IAB) provide guidance in shaping the vision of MTL.

In 2021, MTL hosted its annual IAB meetings with representatives from 10 MIG member companies in attendance. Due to the pandemic, the meetings were held virtually on Zoom. To accommodate different time zones, two sessions were offered: the first on the evening of January 28, and the second on the morning of January 29. Marc Baldo, director of RLE, briefed the IAB members on the RLE-MTL integration, followed by research presentations from selected members of the core faculty. Facilities and IT/CAD updates were then provided, and the IAB representatives participated in a wide-ranging and thoughtful discussion on the current state and the future of computing, nanofabrication research, and facilities at MIT. MIG company representatives attending the meetings included Susan Feindt (Analog Devices), Chorn-Ping Chang and Philip Kraus (Applied Materials), David Carter (Draper Laboratory), George Courville and Anthony Taylor (Edwards Vacuum), Vivek Dave (HARTING), Takanobu Haga and Hiroshi Suzuki (Hitachi High-Tech. Co.), Dirk Pfeiffer (IBM), Nerissa Draeger (Lam Research), Akihiro Kirihara and Tomo Tanaka (NEC), Jim Wieser (Texas Instruments), and Meng-Fan (Marvin) Chang and Chuei-Tang Wang (TSMC).

MIG member companies engage with MTL core faculty, students, and researchers in many ways, including assistance with recruiting events on campus, access to MTL's annual research conference and Microsystems Mini Technical Symposia, faculty visits, and priority access to MTL and MIT.nano resources. One of the unique benefits for member companies is the opportunity to have a scientist or engineer in residence on campus as an active participant in the research activities of an MTL-affiliated faculty member or research center. This past year, there was one MIG member company visitor: Sam Fuller (ADI) worked with Max Shulaker.

Microsystems Mini Technical Symposia

In July 2020, MTL held the inaugural virtual Microsystems Mini Technical Symposium. The featured speakers were MTL core faculty members Jing Kong, Luqiao Lu, Jelena Notaros, and Vivienne Sze. A variety of topics were discussed, including low-dimensional materials, spintronics, integrated photonics, and efficient computing. The event, which was open to the MTL and MIT.nano communities as well as MIG and MIT.nano Consortium members, was recorded and has been made available as a resource to members. It was extremely well received by the members of MIG and MAP. In November 2020 a second virtual Microsystems Mini Technical Symposium was held, with Song Han, Jeehwan Kim, Max Shulaker, and Luis Velásquez-García presenting their groups' research.

Startup@MTL

Startup@MTL, an event initiated by MTL in 2017, hosts MIT spin-off startup companies specializing in microsystems. This event is open to MIG members, and MIT.nano Consortium members were invited beginning in 2021. The purpose of the event is to familiarize MIG and Consortium members with MIT spin-off companies with exciting new technologies. The startup companies also enjoy exposure to leading industry members in microsystems represented by MIG and the MIT.nano Consortium. The 2021 event, held on April 15 and co-organized with the MIT Startup Exchange, featured Accion Systems, JETCOOL, Sweetwater Energy & Bioproducts, Lelantos, Atomic Machines, and Kebotix.

Career Fair

An MTL/MIT.nano joint virtual career fair was held on November 2, 2020, on the Brazen platform. A total of 79 people registered for the event, and MIG and MIT.nano Consortium companies were invited to participate.

Microsystems Annual Research Report

As with the Microsystems Annual Research Conference, which has been administered and sponsored jointly by MTL and MIT.nano since 2020, the Microsystems Annual Research Report has become a joint effort between MTL and MIT.nano.

The 2021 MTL/MIT.nano joint Microsystems Annual Research Report represented a broad cross section of the MIT community, with nearly 40 faculty members and 118 students, postdoctoral associates, and research staff participating. The 118 abstracts were organized into seven topical areas:

- Biological, Medical Devices, and Systems
- Circuits and Systems for Communications, Internet of Things (IoT), and Machine Learning
- Electronic, Magnetic, Superconducting, and Neuromorphic Devices
- Machine Learning, Neural Networks, Artificial Intelligence (AI)
- MEMS, Field-Emitter, Thermal, and Fluidic Devices
- Nanotechnology, Nanostructures, Nanomaterials
- Photonics and Optoelectronics

The 2021 Microsystems Annual Research Report shows a broad range of insights and innovations that emerge from the MTL community and users of MIT’s shared facilities.

Microsystems Annual Research Conference

For 17 years, the Microsystems Annual Research Conference, sponsored by MTL (and sponsored jointly with MIT.nano since 2020), has brought together an audience of over 200 people every January for a two-day exploration of research achievements (the MARC summary provided here was contributed by Amanda Stoll of MIT.nano). A gathering that prizes personal interactions as much as academic presentations, MARC traditionally takes place in New Hampshire, where skiing, snowshoeing, and social activities are intermingled with poster sessions and technical talks.

This year the pandemic was the major challenge faced by student co-chairs Jessica Boles and Qingyun Xie. The two student co-chairs convened a committee of 16 students who, over 10 months, managed responsibilities such as reviewing abstracts, finding keynote speakers, and organizing social activities while also navigating new hurdles—selection of an online platform, concurrent virtual poster presentations, physical and digital distribution of materials, and online networking.

MARC 2021 was held on Gather, an online platform with the look and feel of a retro video game in which attendees use their keyboard to navigate a virtual space as digital characters. Participants could "bump into" other conference goers, sit at virtual tables to eat lunch together, settle into pixelated armchairs for discussions, visit an auditorium with a center stage for lectures, and browse a poster session hall—all reminiscent of a traditional MARC.

The selection and design of this virtual setting was just one of the many tasks accomplished by the student core committee members, who broke responsibilities into six categories. Outreach efforts were led by Sarah Muschinske (EECS), conference package design and execution by John Niroula (EECS), website and proceedings by Jatin Patil (DMSE), communications training by Nili Persits (EECS), social/networking activities by Kaidong Peng (EECS), and conference platform by Haoquan Zhang (EECS).

Keeping attendees engaged was a high priority for the MARC committee, and the group's efforts proved successful. A record-breaking 327 individuals attended the conference, which was held on January 26 and 27 and was open to MIT students, faculty, and members of MTL's Microsystems Industrial Group and MIT.nano's Consortium. MARC 2021 featured 87 student abstracts from over 30 research groups, on par with student presentations from previous years. A networking lunch for students and industry partners—a traditional highlight of the in-person event—attracted 87 attendees.

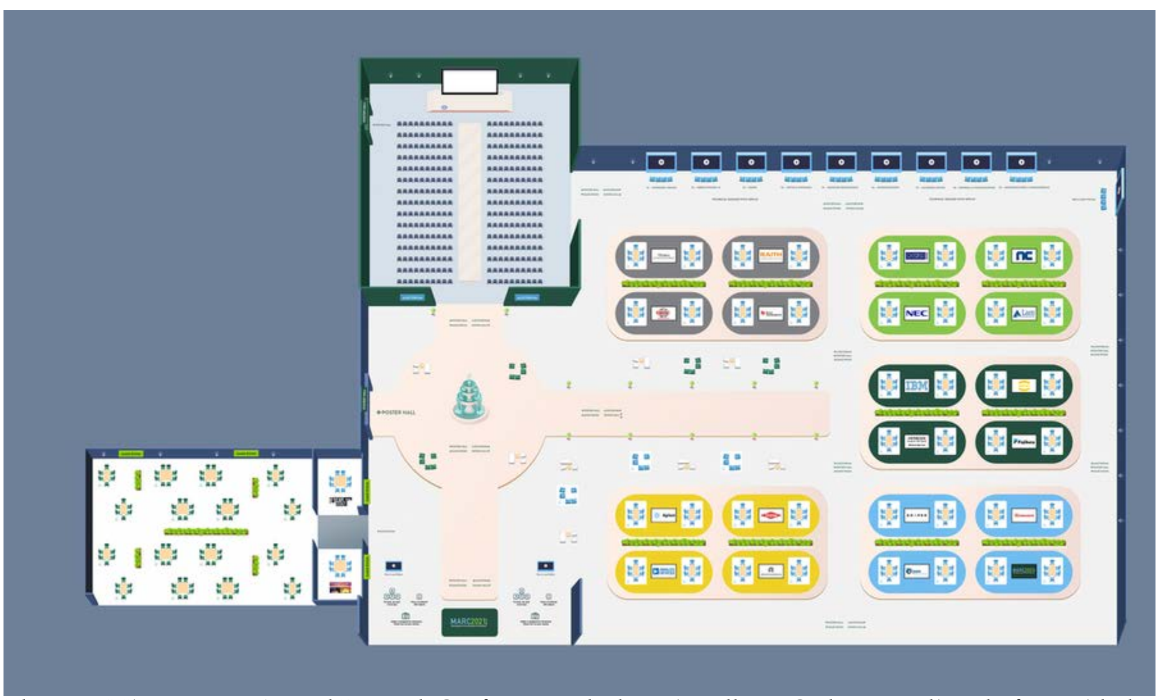
A student-run comedy show replaced traditional winter sports. Evening social activities included online games and a virtual escape room. A new series of MIT faculty rap sessions was added this year following each technical block and moderated by a MARC student committee member. To preserve a tangible aspect to the conference, attendees received a package in the mail containing, among other items, a face mask with a nano-silver filter, a chocolate bar featuring the Boston skyline, and a handwritten postcard from the co-chairs. Conference meals were also provided via online ordering.

One benefit of the virtual format was that keynote speakers could join from anywhere in the world as long as they had an internet connection. Irwin Jacobs, founding chairman and CEO emeritus of Qualcomm Inc., opened the conference from California with a fireside chat with MIT PhD student Kruthika Kikkeri about his time working in academia and why he decided to move into the startup world. Jacobs offered words of advice to entrepreneurs thinking about starting their own business.

MIT student research was presented over the course of the two days through pre-recorded pitches and virtual poster sessions broken into three technical blocks, each containing three research categories. Topics included quantum technologies, power, electronic devices, biotechnologies, energy-efficient AI, nanostructures and nanomaterials, integrated circuits, optics and photonics, and COVID-19. Each category was carefully curated by an EECS graduate student session chair who reviewed abstracts and digital posters, providing feedback and ensuring that all deadlines were met. The 2021 session chairs were Eric Bersin, Benjamin Cary, Nadim Chowdhury, Kruthika Kikkeri, Jane Lai, Ting-An Lin, Elaine McVay, Rishabh Mittal, and Milica Notaros.

The second day's keynote was replaced with a special session featuring lightning talks that showcased technologies being developed at MIT that are applicable to the fight against COVID-19 or similar threats in the future.

Adam Wentworth, a research affiliate at the Koch Institute, and Sirma Orguc, a postdoctoral associate from the Institute for Medical Engineering and Science, presented the TEAL respirator, an N95 alternative with a flexible fit and health and environment monitoring sensors. RLE postdoctoral associate Dohyun Lee discussed rapid monitoring of sepsis using microfluids. Kikkeri, a PhD student in Joel Voldman's research group, presented an at-home sensing platform that could be used for sensitive and rapid measurement of protein biomarkers. Michael Specter, a PhD student in the Computer Science and Artificial Intelligence Laboratory, explained SonicPACT, an ultrasonic ranging method for contact tracing and exposure notifications. Finally, Mantian Xue and Jiadi Zhu, PhD students from Tomás Palacios's research group, described new bioelectronic sensing technology for fast, accurate COVID-19 screening and ultraviolet-C light for human-friendly sanitizing, respectively.



The 2021 Microsystems Annual Research Conference took place virtually on Gather, an online platform with the look and feel of a retro video game.

Irwin Jacobs, founding chairman and CEO emeritus of Qualcomm Inc., gave the keynote speech at MARC 2021.

Research Centers

Three centers affiliated with MTL provide an opportunity for MIG member companies and other companies to become engaged in focused research initiatives: the Center for Integrated Circuits and Systems (CICS), the Medical Electronic Device Realization Center (MEDRC), and the MIT-MTL Center for Graphene Devices and 2D Systems (MIT-CG).

The mission of the Center for Integrated Circuits and Systems is to promote new research initiatives in circuits and systems design, as well as a tighter technical relationship between MIT's research and relevant industry. CICS investigates a wide range of circuits and systems, including wireless and wireline communication, high-speed and RF circuits, microsensor/actuator systems, imagers, digital and analog signal processing circuits, biomedical circuits, and power conversion circuits. Nine faculty members participate in CICS: Director Hae-Seung (Harry) Lee, Anantha Chandrakasan, Ruonan Han, Song Han, David Perreault, Negar Reiskarimian, Max Shulaker, Charles Sodini, and Vivienne Sze. The center provides a unique opportunity for faculty, especially junior faculty, to develop close relationships with industry participants. In FY2021, CICS hosted two virtual research reviews (in November 2020 and May 2021) in which consortium members were invited to participate.

MIT-CG brings together MIT researchers and industrial partners to advance the science and engineering of graphene and other two-dimensional materials. Specifically, the center explores advanced technologies and strategies that enable 2D materials, devices, and systems to provide discriminating or breakthrough capabilities for a variety of system applications ranging from energy generation/storage and smart fabrics and materials to optoelectronics, RF communications, and sensing. In all of these applications, MIT-CG supports the development of the science, technology, tools, and analysis needed to create a vision for the future of new systems enabled by 2D materials.

The vision of MEDRC is to revolutionize medical diagnostics and treatments by bringing health care directly to the individual and to create technology for the future information-driven health care system. The center, launched in May 2011, currently has four member companies (Analog Devices, IBM, Nihon Kohden, and Philips Research) at a funding level of approximately $1.5 million per year. MEDRC serves as a focal point for engagement with researchers across MIT, the medical device and microelectronics industries, venture-funded startups, and the Boston medical community. MEDRC companies strongly support the newly formed IMES Industrial Group (IIG) to broaden industry participation with IMES faculty and students. This year Professors Sodini and Thomas Heldt organized the first meeting of IIG, with all MEDRC members and representatives from Abiomed and Novartis attending.

2021 Research Highlights

Tayo Akinwande

An obvious way to overcome the limitations of Si transistors is to use a vacuum as the device transport channel. There is no scattering (ballistic transport) or impact ionization (channel breakdown) in the vacuum channel. The Johnson figure of merit (JFoM) for nanoscale vacuum channel transistors (NVCTs) is 4.8×10^{14} volts per second, which is 10 times as large as the JFoM for the widest bandgap semiconductor. The breakdown field of the vacuum channel is very high, and the electron velocity does not saturate. This makes NVCTs a candidate for a practical high-frequency and high-power device. A key building block for electronic application is the switch.

Professor Akinwande's group demonstrated for the first time a vacuum transistor based on Si operating in excess of a 38 kV applied bias, a voltage normally reserved for high bandgap materials such as SiC and GaN. This is a proof of concept demonstration of a high-performance vacuum transistor with the potential of having a semiconductor-like footprint. The device consists of a gated field emission array or an electron source, a vacuum drift region, and a metal anode. Electrons are emitted from the gated field emission array into a vacuum through tunneling, travel through the vacuum, and are collected at the anode. In this case, the vacuum determines the properties of transport and the high voltage isolation. The theoretically derived Baliga, Johnson, and power versus frequency figures of merit show the benefits of using a vacuum drift channel, especially for applications that require both high frequency and high power. The origins of the improved performance are the high critical field of the vacuum and, most important, the unbounded nature of the electron velocity due to a lack of scattering.

Based on the results of the high speed and high voltage switch, Akinwande and his group built a high-speed pulsed X-ray source and used it to demonstrate a computed tomography (CT) scanner. Using the pulsed X-ray CT scanner, they took full three-dimensional (3D) images of a pig's lungs and a multimeter. Their analysis showed that it is possible to have a high voltage switch (150 kV) with a current density above 50 A/cm^2. They measured a resolution 0.6×0.6 millimeters from a field emission array device with a size of 0.5×0.5 millimeters, which is a remarkable result because the source size could be changed by the array size in silicon. The group's findings have the potential of changing the architecture of X-ray CT scanners and expanding the application space of CT scanners.

Duane Boning

The research in Professor Boning's group focuses on statistical and machine learning methods to understand, model, and control variations in manufacturing and design, with an emphasis on integrated circuits and silicon photonic processes, devices, and circuits.

In one project, they developed and demonstrated machine learning methods for anomaly detection in time series data from manufacturing equipment. Multivariate time series are increasingly prevalent, with ubiquitous sensing on advanced process equipment; one high-priority need is to use these data streams for early detection when the process is not operating normally. However, often only limited "known good" data are available, so conventional supervised ML methods are not effective. Boning and his group have developed and demonstrated a group of one-class ML-based approaches that use unsupervised learning to build a latent space representation, with recurrent neural network elements in the latent space, to cluster and characterize known-good behavior in that latent space. In collaboration with Harting, Lam Research, and Analog Devices, they have shown that these approaches can be effective with a number of manufacturing tools ranging from plasma etch to milling machines.

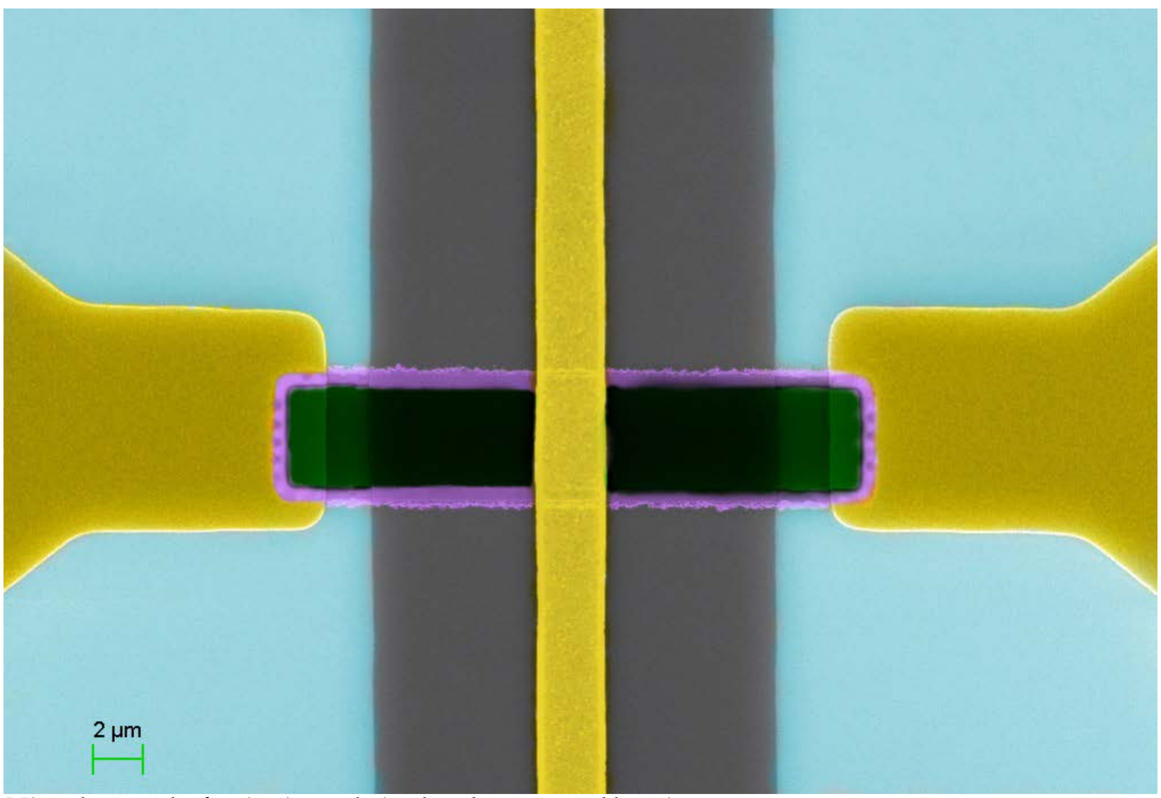
Anantha Chandrakasan

Current sensors play a crucial role in many monitoring and control applications, such as electric vehicle battery management, motor control, solar panel inverters, and power line monitoring. Magnetometers sense the magnetic fields emanating from current-carrying conductors to indirectly measure current, thus providing inherent galvanic isolation for high-voltage applications. Within magnetometers, integrated fluxgate (IFG) sensors offer improved performance over Hall devices, with higher dynamic range, sensitivity, and linearity and lower temperature drift. IFG operation involves driving magnetic cores in and out of saturation, in opposite directions, while sensing the induced voltage difference as a function of the external magnetic field. The devices achieve high linearity by balancing external magnetic fields within the core using compensation current, which makes them power hungry, consuming up to 1 W of power for a three-phase measurement. Moreover, previous IFG sensors were designed for continuous operation at high sampling rates and cannot be duty cycled efficiently due to the long initial convergence time. Professor Chandrakasan's group demonstrated a duty-cycled IFG magnetic-to-digital converter to suit various application needs for power, noise, and bandwidth. The system uses a mixed-signal front end design to enable energy-efficient duty cycling and a 13 b digital integrator to retain the last converged value during sleep and resume searching in its vicinity upon wake up. The system achieves a ±2.4 mT measured range of magnetic fields for indirect current measurement. The hierarchical search modes achieve 10 times faster convergence than analog implementations. The faster readout with a peak sampling rate of 125 kHz is 67% higher than prior fluxgate art, with competitive 500 nT root mean square noise. The test chip fabricated in 250-nm complementary metal-oxide semiconductor (CMOS) technology consumes the lowest power of known IFG sensors. It can be duty cycled to save energy in low-bandwidth applications and run at peak frequency for applications requiring low latency.

Jesús del Alamo

The del Alamo group's most exciting result comes from a collaboration with Bilge Yildiz and Ju Li on a paper titled "CMOS-compatible Protonic Programmable Resistor based on Phosphosilicate Glass Electrolyte for Analog Deep Learning." The lead authors were PhD student Murat Onen from the del Alamo group and postdoc Nicolas Emond.

Ion intercalation-based programmable resistors have emerged as a potential next-generation technology for analog deep learning applications. Proton, being the smallest ion, is a very promising candidate to enable devices with high modulation speeds, low energy consumption, and enhanced endurance. Professor del Alamo and his group have reported on the first back-end CMOS-compatible nonvolatile protonic programmable resistor enabled by the integration of phosphosilicate glass (PSG) as the proton solid electrolyte layer. PSG is a solid electrolyte material that displays excellent protonic conduction as well as electronic insulation characteristics. Moreover, it is a well-known material within conventional Si fabrication, enabling precise deposition control and scalability. The group's scaled all-solid-state three-terminal devices show desirable modulation characteristics in terms of symmetry, retention, endurance, and energy efficiency. Protonic programmable resistors based on PSG, therefore, represent promising candidates to realize nanoscale analog crossbar processors for monolithic CMOS integration. A microphotograph of the device is shown below.

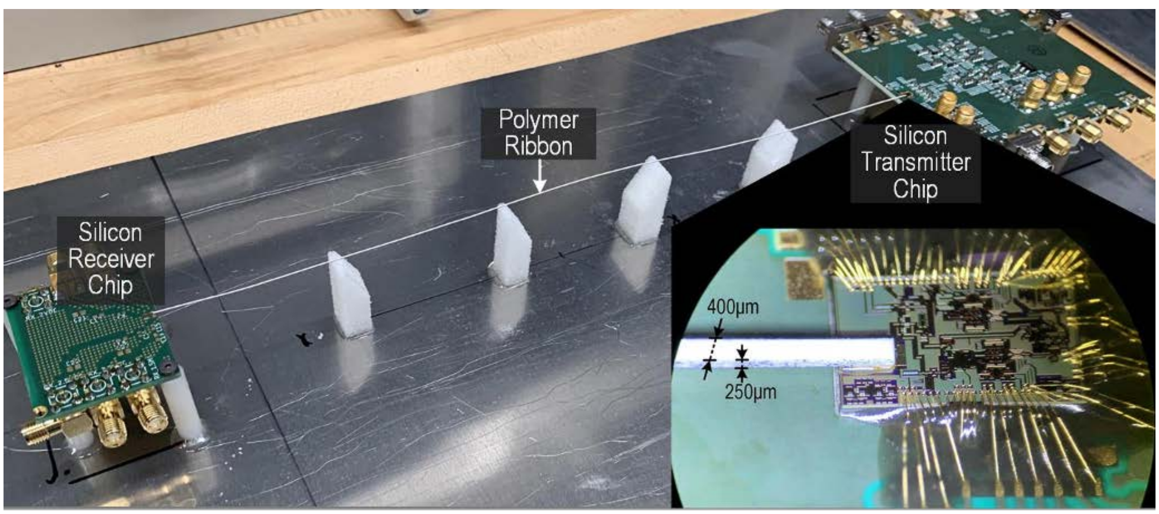


Microphotograph of an ion intercalation-based programmable resistor.

Ruonan Han

The rapid surge of data transmission within computation, storage, and communication infrastructures is pushing the speed boundary of traditional copper-based electrical links. To overcome the excessive signal loss and dispersion of copper wires, recent realizations of 100 Gb per second wireline links require advanced fin field-effect transistor (FinFET) technologies, packaging/cabling with large weight and high cost, and complicated equalization. In contrast, optical links provide high-speed transmission over long distances, but they are typically not compatible with mainstream integrated circuit technologies and their high power consumption and packaging requirement make them unsuitable for short-range, high-link-density applications.

The recent work of Professor Han and his research group combines the mechanisms of electrical and optical links by generating a data-modulated terahertz wave from a silicon circuit chip and transmitting the wave through a dielectric ribbon waveguide. In published work, they demonstrated a 220 to 335 GHz transmitter and receiver chipset using 130-nm BiCMOS technology. Without any external coupler structures, the two chips are directly connected through a 30-cm-long polymer ribbon. Due to the high signal frequency, the cross-sectional area of the ribbon waveguide is only 0.4 × 0.25 mm. With 250 mW power consumption, the chipset achieves a data rate of 100 Gb per second and an energy efficiency of 2.5 pJ/b. The data density figure of merit of this work is 332 Gbps per millimeter, an approximate 12-fold improvement over prior radio frequency (RF) dielectric links. Future applications of the work include meter-class data-centric interconnects with high speed and low latency and lightweight communications within autonomous cars, drones, and other aeronautical vehicles. The test setup is shown below.



Test setup for terahertz link.

Song Han

Modern deep learning requires a large amount of computational resources, engineering effort, and data and a large carbon footprint. On mobile devices, hardware resource and power budgets are very limited, and on-device machine learning is challenging; retraining the model in an on-device manner is even more difficult. Professor Han and his group make machine learning efficient and fit tiny devices (TinyML). They have holistically developed techniques to (1) automatically synthesize efficient and tiny neural architectures given hardware constraints, outperforming the human design while requiring less engineer effort; (2) train their model with tiny amounts of data without losing accuracy, leading to better data efficiency; (3) compress the model and co-design the inference framework to fit tiny devices, including microcontrollers that have only 1 MB of memory; and (4) retrain the model locally on edge devices and customize for new data with tiny memory resources. They have uncovered new design insights under resource constraints. Their research is highlighted by full-stack optimizations, including neural network topology, inference, and hardware architecture, allowing a larger design space to unearth the underlying principles.

This line of research has had significant industry impacts. The group's model compression tools have been integrated in the Xilinx Vitis AI platform, the Qualcomm AI Model Efficiency Toolkit, the Intel Neural Network Distiller, and the Intel OpenVino Toolkit. Their research on pruning and sparse inference engines impacted the design of the Samsung neural processing unit and the NVIDIA A100 graphics processing unit, and their weight pruning and palettization techniques impacted the Apple A12 Bionic neural engine. Their automated neural architecture search technique, ProxylessNAS, has been adopted by Facebook PyTorch and Amazon AutoGluon. This second-generation, once-for-all network consistently outperforms human designs and has ranked first in six finishes of efficient AI challenges at flagship AI conferences. The group's research has received more than 22,000 citations on Google scholar and 9,000 stars on Github and has been cited by well-known research institutes including Google Brain and Facebook AI Research. In addition, their work has been covered in more than 30 press articles in venues such as *IEEE Spectrum*, Engadget, *Wired*, *MIT News*, and Venture Beat and spotlighted twice on the MIT home page.

Harry Lee

Solid-state digital temperature sensors are ubiquitous in many modern systems, including IoT devices. Microprocessors also monitor temperatures in various parts of the circuit for proper thermal management of the processor. Most high-accuracy temperature sensors rely on proportional-to-absolute-temperature (PTAT) voltage, which is converted to a digital value through an analog-to-digital converter (ADC) with a bandgap reference. The bipolar junction transistor–based PTAT source is typically very linear and accurate. However, the temperature dependence of the bandgap reference is finite and nonlinear, necessitating costly individual calibrations at different temperatures.

In collaboration with Anantha Chandrakasan, Professor Lee's group is exploring a new way of sensing temperature accurately that avoids bandgap references and their non-idealities. Temperature is measured with fundamental physical parameters and a single capacitor value only. In this work, they sense thermal noise whose mean square value is fundamentally a linear function of the absolute temperature. The noise is measured via an ADC whose reference voltage is a PTAT voltage. A large number of noise voltages are measured to compute the root mean square value, which is a square root function of the temperature, against the PTAT reference voltage. The result is a temperature sensor that depends on fundamental parameters such as Boltzman's constant, electron charge, and only one circuit parameter C, which is highly accurate. The test chip has been designed, taped out, and fabricated. The group is currently performing preliminary characterization of the device.

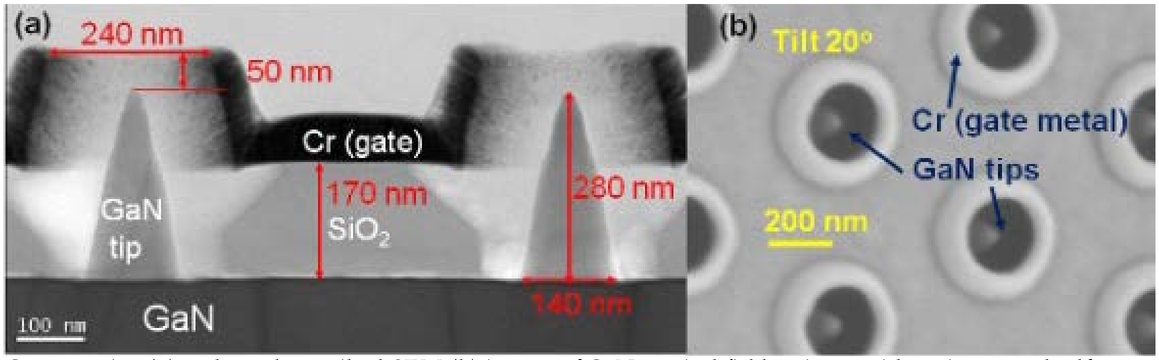
Luqiao Liu

In Professor Liu's group, research has focused on investigating novel spintronic devices and materials. The group's research on the spin current transport phenomena inside antiferromagnets (AFMs) revealed the possibility of using AFMs as building materials for magnonic/spintronic devices. Antiferromagnets have great potential in spintronics because of their immunity to external magnetic disturbance, the absence of a stray field, and their resonance in the terahertz range. The coupling of insulating AFMs to spin-orbit materials enables spin transport via AFM magnons. In particular, spin transmission over several micrometers occurs in some AFMs with easy-axis anisotropy. Easy-plane AFMs with two orthogonal, linearly polarized magnon eigenmodes have unique advantages for low energy control of ultrafast magnetic dynamics. However, it is commonly conceived that these magnon modes are less likely to transmit spins because of their vanishing angular momentum. The group provided experimental evidence that an easy-plane insulating AFM, an α-Fe2O3 thin film, can efficiently transmit spins over micrometer distances. The spin decay length shows an unconventional temperature dependence that cannot be captured considering solely thermal magnon scatterings. Liu and his team interpreted their observations in terms of interference of two linearly polarized, propagating magnons in analogy to the birefringence effect in optics. Furthermore, the devices can realize a bi-stable spin current switch with a 100% on/off ratio under a zero remnant magnetic field. These findings provide additional tools for nonvolatile, low-field control of spin transport in AFM systems.

Tomás Palacios

The solid-state transistors that have made the electronics revolution possible suffer from the relatively poor electronic transport of carriers in a semiconductor channel. The use of a semiconductor channel also limits the high temperature and operating environment of current electronics. Professor Palacios and his group aim to develop a new generation of electronic devices based on gate-controlled field emission of carriers into a vacuum channel. The lack of scattering in a vacuum channel allows for carrier velocities approaching the thermal velocity limit, making these devices ideal for sub-millimeter wave and terahertz applications. At the same time, the lack of a bulk semiconductor channel allows for the use of these devices in the harsh environments of chemical plants, hypersonic flight, or space exploration.

The group's research has pioneered the use of gallium nitride (GaN) and its alloys for three-terminal field emitters. This wide-bandgap semiconductor is ideal as a field emitter thanks to its large density of states and low work function, which maximizes field emission current for low voltages. In addition, its large bandgap increases the robustness and reliability of the fabricated devices. By using novel device designs and fabrication technologies, the group has demonstrated arrays of hundreds of GaN field emitters that have a sub-10-nm tip radius and are controlled by a gate electrode. These devices have been fabricated entirely in MIT.nano and show a current density exceeding $1A/cm^2$, setting the current state of the art for field emission structures based on semiconductor emitters. Further improvements in performance are possible by exploring high-aluminum-composition alloys and alternative crystalline orientations. The group expects the first integrated circuits based on these novel devices to be ready sometime in 2022, opening new opportunities for high-frequency communications, compact X-ray imaging, and electronics for harsh environments. Cross-section and top-down tilted scanning electron microscope (SEM) images of the devices are shown below.



Cross-section (a) and top-down tilted SEM (b) images of GaN vertical field emitters with an integrated self-aligned gate.

Max Shulaker

Professor Shulaker's group has made carbon-nanotube (CNT) devices practical by improving yield and functionality through innovations in both process technology and system design. The group has successfully transferred the CNT technology developed at MIT into a commercial foundry. This past year, they successfully scaled down the technology to a 90-nm node within the foundry and developed all of the design infrastructure needed to enable the foundry to offer a commercial run in the coming year. This commercial run will be the first commercial monolithic 3D tape-out offering integrating conventional silicon CMOS, CNT logic, and resistive RAM within a single chip at a 90-nm technology node.

In addition, Shulaker and his group developed a CNT-CMOS integrated system for biomedical applications. In close collaboration with Massachusetts General Hospital, they have completed the second phase of clinical testing, leveraging their rapid infectious disease sensors. Their chips integrate massive numbers of CNT volatile organic compound (VOC) sensors, enabling the chips to learn and recognize the unique mixture of VOCs generated from patient samples. Thanks to this work, they received the Moore Inventor Fellowship, which will provide additional years of funding for their research.

Luis Velásquez-García

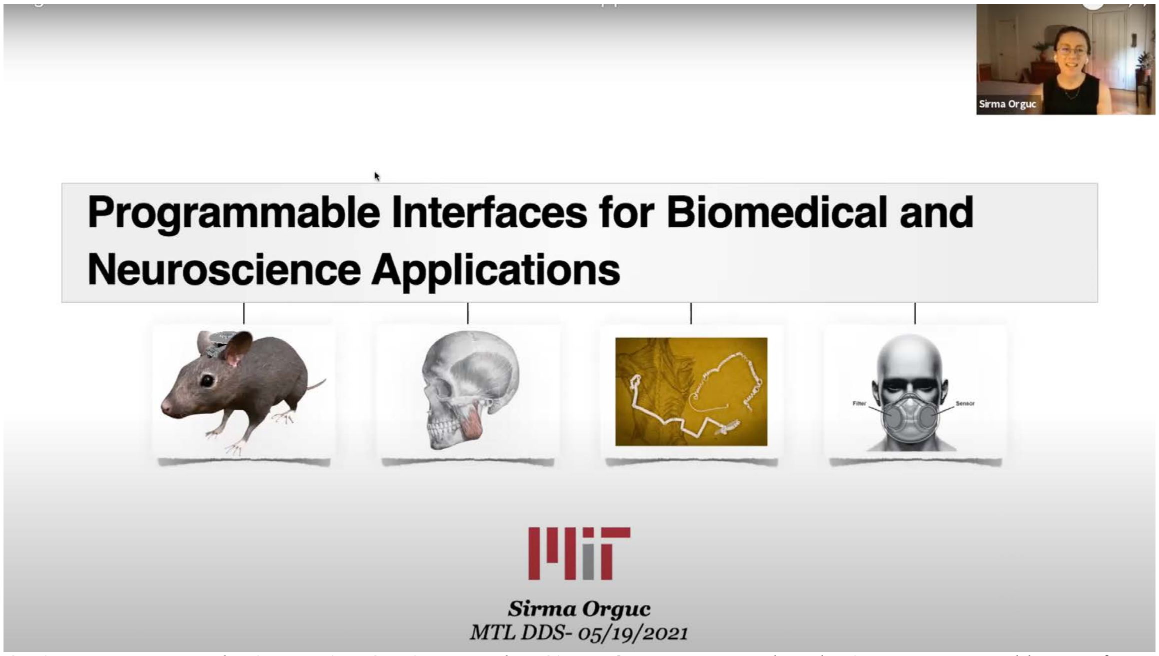
The Velásquez-García group conducts fundamental research on micro- and nanoelectromechanical systems, focusing on harnessing high-electric field phenomena and additive manufacturing. The group, in collaboration with the MIG company Edwards Vacuum, recently demonstrated the first monolithic, fully 3D-printed, multi-material magnetic pumps in the literature. The mini-pumps are fabricated using 150 µm thick to 225 µm thick layers via fused filament fabrication; the structural parts are printed in pure Nylon 12, while the magnet that makes possible the actuation of the pump chamber is printed in Nylon 12 embedded with NdFeB micro-particles. The devices are driven by a rotating magnet and can deliver liquid flow rates as large as 7.88 ml min^{-1}, greatly surpassing state-of-the-art, 3D-printed miniature liquid pumps. Actuation of the pumps in excess of 14.4 million cycles shows no evidence of degradation (e.g., leaks).

2021 Program Highlights

Since 2015, MTL has been hosting faculty members, postdocs, and students under the partnership MIT established with Tecnológico de Monterrey. Since the Tecnológico de Monterrey program is geared toward fabrication, it was decided in late December 2019 to transfer the program from MTL to MIT.nano after a series of discussions among MTL director Harry Lee, former MTL director Jesús del Alamo, MIT.nano director Vladimir Bulović, and Tecnológico de Monterrey representatives Arturo Molina Gutiérrez, Manuel Indalecio Zertuche Guerra, Ricardo Ambrocio Ramírez Mendoza, and Adriana Vargas Martínez. MTL's Luis Velásquez-García has been hosting a number of students, postdocs, and faculty from Tecnológico de Monterrey every summer in a number of separate one-week sessions of the nanoLab hands-on course on nanotechnology. The program was offered in summer 2021 in six sessions with a total of 199 participants.

MTL engages the community in several technical events and programs. In both the fall and spring of each academic year, the laboratory hosts a seminar series spanning diverse technical areas. The seminars are organized by a committee chaired by Luis Velásquez-García, and all seminars are open to the public. In addition to these regular seminars, MTL hosts one Doctoral Dissertation Seminar (DDS) each semester featuring a speaker selected from recent MTL PhD graduates, as well as occasional executive seminars featuring senior leaders from MIG member companies. In December 2020, Taehoon Jeong's dissertation, "Secure Analog-to-Digital Conversion against Power Side-Channel Attack," was selected for DDS presentation. Jeong conducted his PhD work under the supervision of Anantha Chandrakasan and Harry Lee in the Department of Electrical Engineering and Computer Science. In May 2021 the DDS award winner was Sirma Orguc, who presented her dissertation, "Programmable Interfaces for Biomedical and Neuroscience Applications." Orguc conducted her PhD research under the supervision of Anantha Chandrakasan and Professor Polina Anikeeva in the Department of Electrical Engineering and Computer Science.

Fall 2020 Doctoral Dissertation Seminar speaker Taehoon Jeong presents his thesis, "Secure Analog-to-Digital Conversion against Power Side-Channel Attack," on December 2.



Spring 2021 Doctoral Dissertation Seminar speaker Sirma Orguc presents her thesis, "Programmable Interfaces for Biomedical and Neuroscience Applications," on May 19.

Facilities Update

The physical transfer of fabrication equipment to MIT.nano (Building 12) continues. Most of the Exploratory Materials Laboratory (39-5) and all of the lithography tools have been moved, many Technology Research Laboratory (39-4) tools (with the exception of furnaces) are scheduled to be moved during fall 2021, and Integrated Circuits Laboratory (39-2) tools either have been sold (when they were deemed not useful in MIT.nano and MTL faculty members expressed no need for them) or will remain in Building 39 until approximately 2022. All fabrication capabilities in Buildings 12 and 39 are open to all users.

New equipment purchases are being carried out by MIT.nano with input from MTL principal investigators. Although MIT.nano now has administrative responsibility, MTL continues to provide oversight in support of the fabrication research activities of around 360 students and postdocs from inside and outside MIT who represent 138 faculty groups.

As of July 1, 2021, management responsibility for the 17 fabrication staff members will be transferred functionally to MIT.nano (the formal appointments had already been transferred in 2018). MIT.nano is now fiscally responsible for all fabrication operations; MTL's seven-year agreement with MIT.nano to financially support it until 2023 (by providing to MIT.nano $50,000 of the $150,000 MIG membership fee MTL receives from each company) continues.

MTL Outreach and Educational Activities

MTL actively engages in School of Engineering initiatives such as the Undergraduate Research Opportunities Program (UROP) and SuperUROP. SuperUROP and UROP engage MIT undergraduate students and promote direct interaction with faculty and industry sponsors, cultivate student creativity and professional development, and encourage students to consider the ethical and entrepreneurial aspects of their work. In FY2021, nine undergraduate students in the programs worked in MTL.

Awards, Honors, and Promotions

MTL faculty and students regularly receive recognition for their research contributions and accomplishments, with numerous national and international awards. The following awards and distinctions were collected by MTL-affiliated faculty, staff, and students during the reporting period:

- Ruonan Han was promoted to associate professor with tenure.
- Tomás Palacios received the Institute of Electrical and Electronics Engineers (IEEE) George E. Smith Award for his paper "Large-Area 1.2-kV GaN Vertical Power FinFETs with a Record Switching Figure of Merit." This award is given for the best paper (only one per year) published in *IEEE Electron Device Letters* in the previous year. Also, Palacios was awarded the 2020 MIT EECS Faculty Research Innovation Fellowship, was named a 2020 Web of Science Highly Cited Researcher, and received the Intel 2020 Outstanding Researcher Award.
- Polina Anikeeva and William Tisdale were named 2020 MacVicar Faculty Fellows.
- Negar Reiskarimian was named the X-Window Consortium Career Development Chair Professor.
- Kevin O'Brien was named the Emanuel E. Landsman Career Development Professor.
- David Perreault was elected to the National Academy of Engineering.
- Hanrui Wang (a student in Song Han's group) received the 2021 Analog Devices Outstanding Student Designer Award.
- Muhammad Ibrahim Wasiq Khan, Jongchan Woo, Xiang Yi, Mohamed I. Ibrahim, Rabia Tugce Yazicigil, Anantha Chandrakasan, and Ruonan Han received the 2021 IEEE Radio Frequency Integrated Circuits Symposium Best Student Paper Award.

Administrative Updates

MTL's staff is integral to its success and infrastructure. MTL hired a new fiscal officer, Kristin Cook, in February 2021. An experienced research administrator, Kristin reports to both MTL and RLE, and she will help to manage and transfer all faculty financial portfolios as they eventually transition to RLE.

Hae-Seung (Harry) Lee
Director
Advanced Television and Signal Processing Professor of Electrical Engineering