Materials Research Laboratory

The mission of the Materials Research Laboratory (MRL) is to support the broad materials research community at MIT, to promote and enable interdisciplinary research of benefit to society, to develop and sustain effective educational and societal outreach programs, and to develop partnerships with industry.

The MRL was founded in October 2017 by merger of the Materials Processing Center and the Center for Materials Science and Engineering, which had separately served the broad MIT materials research community for over 41 years. The MRL provides a unified nexus for support of interdisciplinary interactions among more than 200 Principal Investigator (PI)–led groups carrying out research on materials within MIT, and it serves as a portal and mediator for engagements with industry, government, and other academic institutions. The MRL partners with MIT.nano and other organizations to provide research environments and tools that promote research breakthroughs. The MRL helps translate breakthroughs to technologies that impact society and communicates to the public the profound role that materials research plays in creating and advancing all of the technologies that affect our daily lives.

In the past fiscal year, the MRL directly supported the research of more than 79 faculty PIs with activities that include materials for energy conversion and storage, spintronics, photonics, metals, integrated microsystems, materials sustainability, solid-state ionics, complex oxide electronic properties, biogels, and functional fibers, as well as fundamental research in condensed matter physics. Support for this research is derived from 117 research contracts, many of which are single-investigator programs. However, as part of its core mission, the MRL also supports formation and administration of interdisciplinary, multi-investigator programs and sub-centers by bringing together faculty from different disciplinary backgrounds, all with a common goal—to produce fundamental new science in materials research.

Multi-Investigator Interdisciplinary Programs and Sub-Centers

The MRL Materials Research Science and Engineering Center (MRSEC), funded by the National Science Foundation (NSF), was established in 1994 as the core program of the former Center for Materials Science and Engineering. The current MRL MRSEC research portfolio includes three Interdisciplinary Research Groups (IRGs):

- Harnessing In-Fiber Fluid Instabilities for Scalable and Universal Multi-dimensional Nanosphere Design, Manufacturing, and Applications
- Simple Engineered Biological Motifs for Complex Hydrogel Function
- Nanoionics at the Interface: Charge, Phonon, and Spin Transport

The MRSEC also includes three seed programs:

- Optical Material Systems to Power the Deep Learning Revolution
- Additively Manufactured Multi-Gradient Metals for Extreme Damage Resistance
- Protonics in Oxides for Novel Quantum, Electronic, and Magnetic Behavior

Altogether the MRSEC grant supported 27 faculty from nine MIT departments. In addition, the MRSEC grant provides funds that help support outreach activities and operations as well as the purchase of new instrumentation for MRL Shared Experimental Facilities (SEFs). The MRSEC program was extended until October 31, 2021. The program will end after October.

Center for Integrated Quantum Materials

The Center for Integrated Quantum Materials (CIQM) is a National Science Foundation Science-Technology Center led by Harvard University, with principal partners at MIT, the Boston Museum of Science, and Howard University. Now in its seventh year, the center focuses on discovering new quantum materials that enable atomic-scale electronics and photonics that transform signal processing and computation. MIT's CIQM effort pulls together 10 PIs from the Departments of Physics and Electrical Engineering and Computer Science (EECS) working in the various fields of quantum materials by design, quantum electronics and photonics, universal quantum interface, and atomic-scale networks. The NSF has renewed the CIQM program for an additional five-year period.

Microphotonics Center

The MIT Microphotonics Center (MPhC) supports research on silicon electronic-photonic system integration that enables the exponential scaling of computational performance and communication bandwidth at relatively constant energy, footprint, and cost. The center faculty benefit from research problem definition with industry and the joint projects that follow. The MPhC conducts technology supply chain studies utilizing a technology working group (TWG) model that involves active participation of members and allied industrial partners from around the world. The TWG studies are commissioned annually by the Microphotonics Center Industrial Advisory Board and are periodically released under the MIT Communication Technology Roadmap (CTR). MPhC key government and NGO partners include the National Institute of Standards and Technology, the International Electronics Manufacturing Initiative (iNEMI), the Institute of Electrical and Electronics Engineers, and the American Manufacturing Institute for Integrated Photonics. The twice annual center meetings became weekly international virtual meetings in 2020 as the MphC engaged the European Union and Asian partners to create a global industry roadmap called Integrated Photonics System Roadmap—International (IPSR-I). The center's technology reach expanded in 2020 with Application Interest Groups addressing technology gaps in data center, RF/5G, lidar, and sensing platforms. Each Application Interest Group conducts an industry-led study to define technology gaps, supply chain requirements, and potential solutions, followed by demonstrator projects under iNEMI management. The 2020 IPSR-I was released December 10, 2020, containing 11 technology and six application chapters.

Materials Systems Laboratory

The Materials Systems Laboratory (MSL) explores the economic and environmental consequences of materials technology choices on manufacturing processes, products, and the supply chains and systems in which those products are used and disposed of. Over this past year, MSL worked across a broad range of topics and industries.

MSL worked with Ford Motor Company to develop machine learning algorithms that mine supplier data to provide new insights into materials-related supply risk. The analysis, published in *Environmental Science and Technology*, showed that vehicle electrification easily doubles the financial exposure of automakers, with an average size firm taking on an additional billion dollars in exposure.

MSL has worked with global mining companies to create a platform to rapidly simulate minerals markets that are transforming from oligopsony to a competitive market, and to model costs associated with a transition to a hydrogen economy especially for the minerals and metals industries.

MSL continues to co-lead the MIT Concrete Sustainability Hub. In this capacity, MSL carried out research to quantify how pavement materials alter the energy use of both vehicles and adjacent buildings. The greenhouse gas emissions from these impacts can be much larger than the materials production emissions. Results from this work were featured in the *Boston Globe*.

In partnership with the Massachusetts Technology Collaborative and the Department of Defense ManTech Office, MSL is leading a road-mapping effort to characterize middle-skilled manufacturing workforce needs for advanced technologies associated with five industries. Roadmaps describe not only what types of workers will be needed but also what skills those workers will need. Results are being used to redesign manufacturing curricula within Massachusetts community colleges.

The Sustainability and Health Initiative for Net-positive Enterprises program (SHINE) at MIT, led by Gregory Norris, continued to pioneer new approaches to drive sustainable practices within manufacturing firms. Three highlights from SHINE activities were projects that identified opportunities in global firms to reduce greenhouse emissions by delivering sustainable transportation, impacting their product distribution supply chains, and developing new markets for a firm's most efficient products. This program is associated with an ongoing parallel activity at Harvard. MIT activities focus on product and process impacts and Harvard activities focus on employee health. SHINE is supported through an industrial consortium.

Manufacturing USA Institutes

The MRL supported MIT faculty engagement with two Manufacturing USA Institutes in FY2021:

- Advanced Functional Fabrics of America (AFFOA)
- Reducing Embodied-energy and Decreasing Emissions (REMADE) Institute

Each institute was founded based on an initial five-year period of funding from the federal government combined with committed greater than one-to-one cost matching contributions from state and local governments, nonprofits, and industry. These institutes have provided new avenues of government-industry-academia interactions manufacturing research and technology transfer combined with education and workforce development programs. The challenges will continue as each institute transitions into a self-sustaining organization following the initial five-year period of federal funding.

The Advanced Functional Fabrics of America is a Manufacturing Innovation Institute located next to the MIT campus whose mission is to enable the transformation of traditional fibers, yarns, and textiles into highly sophisticated, integrated, and networked devices and systems. Launched as a five-year program in 2016 with MIT as the lead institution, AFFOA now operates as a self-sustaining entity with over 130 members from industry, academia, and government. MIT's engagement with AFFOA is led by Professor Gregory Rutledge of the Department of Chemical Engineering. Administered through the MRL, the institute has more than 35 participating faculty members and researchers from across MIT's five schools.

Major research activities over the past year included a Small Business Technology Transfer grant with Technology Holding, LLC (Svetlana Boriskina, MIT PI) to develop a high-strength fabric with excellent cooling capability, based on bio-derived oriented chain polyethylene fibers and synthetic spider silk fibers. A Massachusetts Emergency Response Team grant on "Testing and Alternative Materials Development for PPE" (Gregory Rutledge, MIT PI), and a Coronavirus Aid, Relief, and Economic Security Act grant on "Creating a Blueprint for Manufacturing During Periods of Surge Demand" (Gregory Rutledge, MIT PI) evolved out of shortages of nonwoven fiber materials for personal protective equipment (PPE) during the Covid-19 pandemic, to address the needs for PPE testing, domestic manufacturing, and supply chain robustness.

Major educational activities over the past year included a continuation of the collaboration between Greater Lawrence Technical School (GLTS) and MIT's Edgerton Center (J. Kim Vandiver, MIT PI) to develop an advanced functional fabrics track at GLTS, and the third annual MIT and FIT Workshop on Advanced Functional Fabrics in January 2021, in collaboration with Fashion Institute of Technology (FIT), AFFOA, and MIT (Gregory Rutledge, MIT PI). This workshop brought together junior/senior undergraduates in engineering and fashion design to solve industrial challenges using advanced fiber and fabric technologies. The January 2021 workshop was conducted fully remotely for the first time. In early August 2021, MIT and FIT signed a collaboration agreement to continue the workshop activities.

A diverse group of 14 MIT researchers from the MRL community prepared a letter of intent in response to MIT's Climate Grand Challenges and was selected to submit a white paper titled "Emissions Reduction through Innovation in the Textile Industry." More information can be found on the Climate Grand Challenges website.

The Institute for Reducing Embodied-energy and Decreasing Emissions, based at Rochester Institute of Technology and led by the Sustainable Manufacturing Alliance, is one of the most recent of the Manufacturing USA Institutes launched in 2017. It will leverage federal funding of $70 million provided over the first five years—matched by an additional $70 million in private cost-share funding from industry and other organization members—and has more than 85 participants in a tiered consortium membership model. The institute is focused on driving down the costs of technologies essential to reuse, recycle, and remanufacture materials such as metals, fibers, polymers, and electronic waste, with the objective of achieving 50% improvement in overall energy efficiency by 2027.

The MRL supports Professor Elsa Olivetti as the lead PI for MIT's membership and interaction with REMADE and is coordinating MIT faculty proposals and administration of program awards. Professor Olivetti is actively working with the REMADE organization and with other professors at MIT, collaborators at other institutions, and with industry to respond to calls for proposals. She received an award in February 2020 for her proposal "Identifying Strategies to Maximize Benefit of Fiber Recovery through Systems Quantification." Her research leverages an existing, industry-vetted modeling approach developed at MIT with existing data and tools to create dynamic and probabilistic analyses and simulation models that will provide a comprehensive, statistically robust estimate of fiber recovery technologies and scenarios. This research includes collaboration with the American Forest and Paper Association.

Singapore-MIT Alliance for Research and Technology Interdisciplinary Research Groups

The MRL supported two Singapore-MIT Alliance for Research and Technology (SMART) IRGs in FY2021:

- Low Energy Electronic Systems (LEES)
- SMART Critical Analytics for Manufacturing Personalized-Medicine (CAMP)

The Singapore-MIT Alliance for Research and Technology Low Energy Electronic Systems Interdisciplinary Research Group is directed by Professor Eugene Fitzgerald, who is also the SMART CEO. The SMART LEES program, in its tenth and final year, involves five MIT faculty members and an MIT senior research scientist as well as their students and postdocs based at MIT. Eleven faculty from Nanyang Technological University and National University of Singapore are also involved in collaborative research. Approximately 20 MIT staff and postdocs are supported in Singapore for research based there.

The goal of the LEES program is to demonstrate practical approaches to integration of compound semiconductor devices with conventional Si-based integrated circuits. Compound semiconductor devices have superior properties for use in photonic and power devices compared to silicon. These devices include solid state lasers, light emitting diodes, and high-power high-electron mobility transistors. Mature silicon integrated circuit technology provides capabilities for high-performance computation and data analysis. Integration of compound semiconductor devices with silicon circuits will enable technologies for:

- High-speed communication within and between circuits
- Advanced displays and lighting made smart through integration with silicon-based control circuits
- Improved wireless communication technologies
- On-chip power management for low power circuits to be used in mobile technologies

The SMART Critical Analytics for Manufacturing Personalized-Medicine Interdisciplinary Research Group IRG, together with the Agency for Science, Technology and Research (A*STAR) Institutes (supported by the National Research Foundation), launched a national initiative in Singapore for cell manufacturing as a new interdisciplinary research group that focuses on ways to produce living cells as medicine delivered to humans, leading to improved health outcomes. The National Research Foundation is supporting this multimillion-dollar, multiyear project that brings together 35 MIT and Singapore investigators recruited from researchers working in SMART and Singapore institutes, including A*STAR, KK Women's and Children's Hospital, the National University Hospital, and local universities. SMART CAMP is led by professor and associate provost Krystyn Van Vliet from MIT and Professor Hanry Yu of National University of Singapore and A*STAR. It will involve 15 MIT faculty members from multiple departments.

CAMP currently has three flagship projects focused on the following:

- Label-free critical quality attributes for personalized efficacy of cell therapies, including multivariate analysis of biological and biophysical attributes
- Rapid critical quality attributes for safety of cell sources and cell therapy products, informing process analytic technologies and speeding product release
- Process analytic technologies for cell proliferation and recovery, including inline and intermittent monitoring to promote efficacy and safety attributes for timely cell product release

Industry Interactions

MRL supports faculty research efforts with industry collaborations over a wide range of materials and science-based applications, from metallurgical coatings for strength and corrosion resistance, integrated semiconductors for opto-electronics (including integrated photonics for communications), sensors, solar cell applications, ceramics (including metal oxides for batteries and fuel cells), to novel 2D materials and topological insulators. MRL, working with faculty, will facilitate interactions between MIT and the company. MRL also provides program management support as needed and will seek to engage the individual companies for future development of research.

During FY2021, MRL supported many ongoing research programs with industry, including: Advanced Functional Fabrics of America, Applied NanoFemto Technologies, Allegheny Technologies, Apple, Draper Laboratories, Ford, Microsoft, Mitsubishi Materials, NCSOFT, NGK Spark Plug, Novelis, Radiation Monitoring Devices, Rio Tinto and Samsung Advanced Institute of Technologies, Rochester Precision Optics, Semiconductor Research Corporation, and SNCF Mobility.

MRL also supports faculty with the establishment and operation of consortium research programs with industry. Three ongoing programs for FY2021 include the Materials Systems Laboratory, Sustainability and Health Initiative for NetPositive Enterprise, and the Microphotonics Center.

New research programs with industry for FY2021 include Ericsson, Global Energy Interconnection Research Institute, International Business Machines, National Institute of Aerospace, Nippon Telegraph and Telephone, and Pendar Technologies.

A collaborative effort was initiated in FY2020 with Professor Vladimir Bulović of MIT.nano and its company member NCSOFT. MRL supports several faculty seedling research awards for their proposals addressing sensors, 3D/4D data interaction and analysis, augmented and virtual reality, and gaming. The recent award recipients include Professors Mohammadreza Alizadeh Attar, Luca Daniel, Frederic Durand, Jeehwan Kim, William Oliver, Jay Scheib, and Justin Solomon.

MRL partners with the Office of Corporate Relations' Industrial Liaison Program (ILP). Support from the MRL includes coordinating with faculty and ILP officers for meetings and providing technical briefings and seminars.

Industry Collegium

MRL Industry Collegium membership benefits include hosting of a staff member for short- or long-term visits, hosting company staff for on-campus visits and company-specific events with MIT students and faculty, assistance in the development of customized research collaborations, and discounted fees for use of the MRL materials characterization.

External Advisory Board

The annual, full-day meeting of the MRL External Advisory Board (EAB) was held via Zoom this year due to the Covid-19 pandemic. Activities from the previous year were highlighted and goals for the new year were discussed. Board members represented 3M Corporate Research Laboratory, the University of Michigan, Allegheny Technologies, BASF Corporation, Harvard University, Lockheed Martin Space Systems, Raytheon Technologies Research Center, Saint-Gobain High Performance Materials, Sandia National Laboratories, Semiconductor Research Corporation, The Boeing Company, The Dow Chemical Company, and the wTe Corporation. The board meeting culminated in an oral and written report to the vice president for research. Additional meetings were held over the course of the year, with individual and groups of EAB members, to discuss specific topics, such as improved and new mechanisms for industrial engagement.

Shared Experimental Facilities

MRL Shared Experimental Facilities (SEFS) are a critically important resource to the MIT research community, as well as serving a number of outside academic and industrial organizations. The three major facilities are Materials Analysis, Electron Microscopy (EM), and X-ray Diffraction. During FY2020, more than 1,020 unique users made use of these facilities, representing 24 MIT departments, labs, and centers, 14 outside academic units, and 15 outside commercial units. Due to Covid-19 restrictions, external user access was restricted and usage by internal users was greatly reduced compared to the prior year. During summer 2021 however, lab use, as measured by user fee revenue, returned to pre-Covid levels. Demand for MRL SEFs instruments remains high, even in light of the impact of pandemic-driven restrictions imposed over the past year on building entry, room capacity, and campus access time limitations.

An exciting development during FY2021 has been the preparation for and implementation of a transition of the MRSEC SEFs to free-standing MIT service centers, decoupled from the MRSEC grant. After detailed, months-long analyses of costs and revenue, synergies and best practices, it was decided to propose two new MIT service facilities: the Electron Microscopy facility, and the Materials Analysis and X-ray (MAX) facility, which combines two previously separate SEFs into a single facility with complementary capabilities. The service center transition was successfully completed as of July 1, 2021.

In addition, MRL empaneled a new MRL SEFs Faculty Advisory Committee, comprising eight faculty members from seven departments across the School of Science and School of Engineering. This committee was charged with assessing and advising on the current state of the MRL SEFs and the future evolution of the facilities, including operational issues, equipment acquisition and renewal, and complementarity with other shared facilities across MIT. A detailed report on the committee's findings is expected at the end of summer 2021.

Beyond the special role the SEFs play in the training and education of MIT students, they are also an important part of the MRSEC education and outreach programs. Students in the summer Research Experiences for Undergraduates (REU) program and community college students use the SEFs to conduct their research. Teachers in the Materials Research Experience for Teachers program spend one morning each week learning about the capabilities and research applications of the equipment in the SEFs. Due to Covid restrictions, there were no in-person MRSEC summer programs in summer 2020. During summer 2021, a virtual REU and community college program was conducted. The MRSEC also supported a virtual Energy Week event, delivered by Professor Steven Leeb, which involves 19 external undergraduate women through the Women's Technology Program (WTP) and 10 K–12 teachers through the MIT-MRSEC Science Teachers Enrichment Program.

As part of a focus on upgrading the scanning probe microscopy facilities, a new Bruker Dimensions atomic force microscope has been installed. It provides a wide array of scanning modes for topographic, electronic, mechanical, and magnetic characterization. Also, a new scanning probe experimental setup for near field infrared nanoscopy and spectroscopy measurements is under development by Professor Long Ju of the Department of Physics.

With funding from MRL and the vice president for research, renovations to the sample preparation room, the shared common area, and the auxiliary space in the EM facility were completed during the spring. This much-needed upgrade provided new casework for the sample prep room, new floors and lighting for the hallways, and a new common area for presentations. Two space renovations were also completed to house a combined in situ FIB-SEM and a highly customized ultra-high-vacuum transmission electron microscope (UHV TEM) with sample manipulators, and an in situ gas environment brought to MIT from IBM by Materials Science and Engineering faculty member Professor Frances Ross. These tools will be integrated into the EM facility following a two-year transition period, leading to assisted use shared facilities in collaboration with a world-leading electron microscopist. The new tools include unique in situ experimental capabilities not available elsewhere.

The MIT MRSEC continues to actively participate in the Materials Research Facilities Network program, facilitating SEFs access for researchers from other universities, particularly those with limited research tool sets and those serving historically underrepresented groups. Access involves submission of a short proposal outlining the analysis to be done and its impact on the proposer's research program and, if relevant, educational activities. During this period Professor Mary Christiansen (University of Minnesota at Duluth) and two others in her group utilized our Analytical, EM, and X-ray diffraction facilities and Professor Kimberly Stieglitz (Roxbury Community College) brought students from her course, Research Science, to our X-ray facility.

Interactions with MIT.nano

Since the formation of MRL we have worked closely with MIT.nano to coordinate and plan collaborative activities, including the utilization of research areas based on equipment performance requirements. MRL is represented on the MIT.nano leadership team by Professor Carl Thompson and on the Tool Committee Subgroup on Metrology by Professor Geoffrey Beach. MIT.nano director Vladimir Bulović serves on the MRL Internal Advisory Board. Bulović, Thompson, and Beach are in ongoing discussions to identify other modes of collaboration to support the missions of both organizations.

MIT.nano has unique capabilities in terms of electromagnetic and vibration isolation providing enhanced performance for some materials characterization systems. This has enabled acquisition of materials characterization equipment, such as an aberration-corrected scanning transmission electron microscope. The MIT.nano materials characterization facilities are operated in close coordination with the MRL facilities, ensuring that the tool sets in the two laboratories serve complementary functions and that booking and billing processes are similar.

Outreach

MRL does not limit its educational outreach to the MIT community. We have worked hard to establish a wide-reaching and diverse portfolio of programs that are both innovative and responsive to the needs of students and educators. The MRSEC has put in place a broad range of well-received programs that impact high school students and teachers, as well as undergraduate and graduate students.

Materials Research Experience for Teachers

For the past 21 years, the MRSEC has operated a successful Research Experience for Teachers (RET) program, which brings high school and middle school teachers to MIT to participate in MRSEC research. Teachers spend seven weeks immersed in research during the first year of the program and are invited to return the following summer for a flexible period of time devoted to developing material that transfers their research experience into classroom teaching. Major components of the program include research, weekly discussions, tours of the SEFs, and the development of classroom materials. An important goal of the program is to document the materials developed by the teachers to be shared with other educators. Lesson plans written by the teachers are distributed to other science teachers and used in teacher workshops. Due to Covid restrictions, the MRSEC was unable to host the RET program during summer 2020.

Community College Program

MRL MRSEC collaborates with Roxbury Community College and Bunker Hill Community College, two minority-rich two-year colleges in Boston, to make research experiences available to its students. The objective of this program is to engage community college students in current materials research and encourage them to pursue careers in science and engineering. Due to Covid restrictions, the MRSEC could not host a Community College Program in the summer of 2020. Four students, two from Roxbury Community College and two from Bunker Hill Community College, were hosted virtually during summer 2021.

Partnership with Universidad Metropolitana

In 2008, we formed a collaboration with Juan Arratia at Universidad Metropolitana to enhance the research experience of students at the three Puerto Rican universities affiliated with the Ana G. Méndez University System (Universidad Metropolitana, Universidad del Turabo, and Universidad del Este). Arratia refers students to the summer Research Experiences for Undergraduates program. At least two intern positions a year are set aside for these students. The partnership is to recruit and retain Puerto Rican science, technology, and engineering graduates. Since the inception of the program, 25 students have participated in the intern program and an additional two students spent two weeks at MIT working with graduate students to learn to use research instruments in the SEFs. As of our last inquiry, of the 25 students, four are still completing their undergraduate studies. Another eight have proceeded to graduate school, one has completed her PhD. Seven others completed their bachelor's degrees and are employed: five as engineers, one in manufacturing, and one as a technology consultant. Due to Covid restrictions, the MRSEC could not host any interns from this program during summer 2020, however two students will be hosted virtually during summer 2021.

Science Teacher Enrichment Program

The MRL MRSEC offered its Science Teacher Enrichment Program (STEP) for the 19th time in summer 2019. STEP—subtitled Dustbusting by Design—is a one-week workshop focused on increasing middle and high school teachers' content knowledge and providing them with experience in engineering design. The workshop correlates to the Massachusetts state science learning standards. Participants spend three and a half days in a machine shop on campus learning about the design challenges associated with the motor in a handheld vacuum, then immersing themselves in the reengineering design process as they construct motors of their own. The lab portion of the program is simultaneously taught to 40 high school girls in the Women's Technology Program. Participants in STEP receive a small stipend and professional development hours. They are recruited from local school districts, from former applicants to the RET program, and through other MIT-based programs for educators. Eight teachers participated in the 2019 STEP program. Due to Covid restrictions, the MRSEC could not host the STEP program during summer 2020. However, a virtual program utilizing the same content described here will be organized by Professor Steve Leeb for 10 teachers from around the United States for 2021.

A companion effort to STEP is the MRSEC's collaboration with the Women's Technology Program in EECS (WTP-EECS), a four-week summer residential program for 40 high school girls from across the country during which participants take classes in math, computer science, and engineering. The program is designed to address a gender imbalance in the field of engineering by increasing the girls' interest and confidence in pursuing engineering careers. The MRSEC invites the WTP-EECS participants to join in the lab portion of STEP to gain hands-on engineering experience. WTP-EECS alumni report that this motor building lab is an exciting part of the program. The MRSEC continued to support WTP-EECS by providing the curriculum and supplies for this part of their program in 2019. A group of these students will join the STEP program virtually during July 2021.

Science and Engineering Program for Middle School Students

The MRSEC program has operated a science and engineering program for seventh- and eighth-grade students from two Cambridge public schools for the past 28 summers. The objectives of the program are to introduce students to the field of materials science and engineering, demonstrate that science and engineering can be fun, and provide students with an opportunity to experience a college environment. The program consists of a full week of hands-on and inquiry-based science and engineering. During summer 2019, 15 seventh- and eighth-grade students attended with their science teachers. The students participated in hands-on activities presented by faculty, staff, graduate students, and undergraduates. The 2019 program included classes on UV light, simple DC motors, electric circuitry, polymers, glass blowing, metal casting, and solar cells. Due to Covid restrictions, the MRSEC could not host this program in summers 2020 and 2021.

Summer Research Internship Program

For 38 years, MRL has sponsored the summer internship program for promising undergraduate researchers from other colleges and universities nationwide. The MRL summer internship is a National Science Foundation Research Experience program for undergraduate students. The program brings the best science and engineering students in the country to MIT for graduate-level materials research in laboratories of participating faculty. The program culminates in a poster session where students present their research to the MIT community.

The 2021 eight-week program ran from June 9 to August 13 and involved 15 faculty members. The program this year was changed to an online format due to the ongoing Covid-19 pandemic. Eleven students were selected from among 173 applications. The students come from schools such as Florida Gulf Coast University, Interamerican University of Puerto Rico at Bayamón, Montana Technological University, Pennsylvania State University, Purdue University, University of California at Berkeley, University of Mary, University of Michigan, University of Pennsylvania, and University of Puerto Rico.

Materials Day Symposium

Sharing knowledge and insight with others in the materials science and engineering fields can lead to new ideas, collaborations, and breakthroughs. Once a year, the materials community is invited to the Materials Day Symposium and Poster Session,

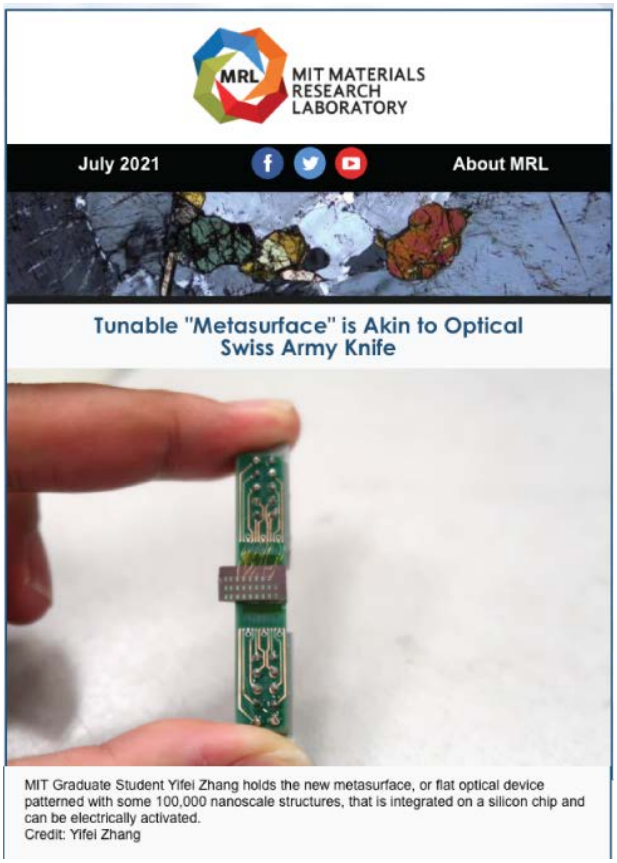
a celebration to recognize and honor the many important accomplishments and achievements of the past year and to talk about the future.

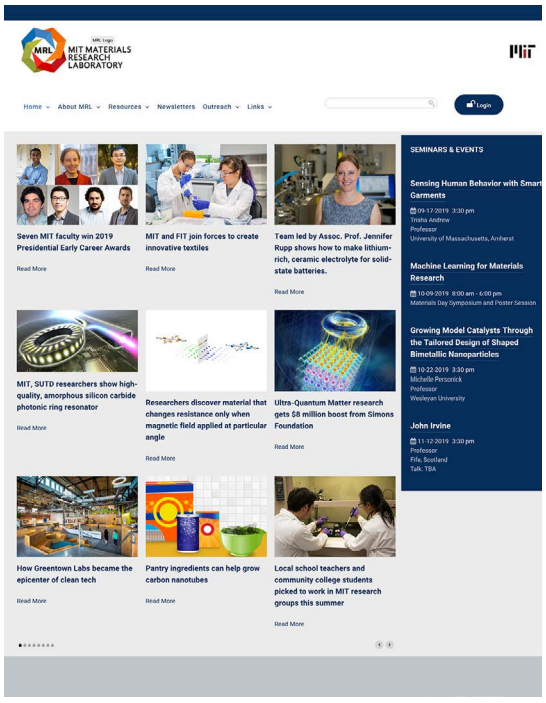
Held in the fall, Materials Day is normally a daylong symposium on a featured topic related to materials science and engineering, followed by a graduate student/postdoctoral associate poster session. This year the Materials Day Symposium and Poster Session were held virtually via Zoom with morning and evening sessions for US and international attendees. The Materials Day 2020 Symposium, Advanced Materials Research for Breakthrough Technologies, consisted of four sessions held over four weeks. Each session included presentations by MIT faculty members, followed by discussions and breakout poster presentations by students and postdoctoral associates. The four sessions and faculty speakers were:

- "After Moore's Law," by Eugene A. Fitzgerald and Jesus del Alamo
- "Spintronics: Putting a Spin on Electronics for Low-Power Computing," by Geoffrey S. D. Beach and Marc A. Baldo
- "Microphotonics Everywhere," Juejun Hu and Rajeev Ram
- "Digital Transformation in Metals Processing," by Chris A. Schuh and John Hart

On average there were approximately 250 attendees in each of the four sessions, with 70% of the attendees being from industry.

Communications





Figures 1 and 2: The MRL e-newsletter sent out monthly and the MRL website homepage featuring news and announcements.

The MRL works with departments and centers across MIT to effectively communicate research, faculty, graduate student, and postdoc accomplishments through a common storytelling lens. By sharing the groundbreaking work our postdocs and faculty do every day across a wide variety of media and through a variety of channels, we create compelling stories. Our goal is to deliver a steady cadence of content through the website, monthly newsletters, and social media. The website is updated daily. It highlights news stories generated for our e-newsletter as well as related news from the MIT News Office and the MIT community.

Promotions and Selected Honors and Awards

MRL faculty received numerous awards and honors. Of special note are:

Professor Tomás Palacios of the Department of Electrical Engineering and Computer Science won Intel's 2020 Outstanding Researcher Award. Annually, Intel recognizes the exceptional contributions made through Intel university-sponsored research. In collaboration with Cornell, the team "seeks a high-performance wide-bandgap PMOS solution for use in RF, power electronics, or digital/analog applications. The team looks to provide a holistic pFET solution through materials innovations, device processing, fabrication, and testing, as well as the development of transport and device physics and compact models, circuit models, and demonstration."

Associate Professor Elsa Olivetti of the Department of Materials Science and Engineering was selected as a 2021 MacVicar Faculty Fellow. The program recognizes exemplary and sustained contributions to undergraduate education at MIT. "Olivetti's research addresses environmental issues such as sustainability, recycling-friendly materials, and waste disposition, which have significant real-world implications."

Pablo Jarillo-Herrero, Cecil and Ida Green Professor of Physics, is the recipient of the 2021 National Academy of Sciences Award for Scientific Discovery for his pioneering developments in nanoscience and nanotechnology. The biennial award recognizes "an accomplishment or discovery in basic research, achieved within the previous five years, that is expected to have a significant impact on one or more of the following fields: astronomy, biochemistry, biophysics, chemistry, materials science, or physics." Jarillo-Herrero was also awarded the Lise Meitner Distinguished Lecture Medal, and the Spanish Royal Physics Society Medal (which is the highest scientific recognition of the organization), for his groundbreaking work on so-called twistronics, a technique that adjusts the electronic properties of graphene by rotating adjacent layers of the material.

Professor Geoffrey Beach of the Department of Materials Science and Engineering and co-director of the MRL, was named a fellow of the American Physical Society on September 28, 2020, for "pioneering contributions to the understanding of chiral exchange interactions, spin-orbit torques, domain wall and skyrmion dynamics in magnetic thin film materials, heterostructures, and nanostructures."

Professor Yet-Ming Chiang of the Department of Materials Science and Engineering was named a fellow of the Electrochemical Society. His work has emphasized using "clean energy technologies such as non-aqueous and aqueous batteries for transportation and grid-scale storage, and most recently, electrochemical production of construction materials."

Research Volume

Total expenditures under MRL totaled $20.9 million in FY2021. Research expenditures from sponsored programs totaled $19.3 million, a slight decrease of 0.18% from FY2020.

Major program expenditures included:

- Professor Geoffrey Beach and the multi-investigator Materials Research Science and Engineering Center, funded by the NSF
- Professor Raymond Ashoori's and 11 co-PI's Center for Integrated Quantum Materials with Harvard University, supported by the NSF, and his program 2D Topological Insulators, supported by the Department of Energy (DOE)
- Professor Eugene Fitzgerald's and eight co-PI's Low Energy Electronic Systems program within SMART
- Professor Krystyn Van Vliet's and eight co-PI's Critical Analysis for Manufacturing Personalized-Medicine program with SMART
- Professor Krystyn Van Vliet's and her five co-PI's program Chemo-Mechanics of Far-from-Equilibrium Interfaces, supported by the DOE
- Professor Geoffrey Beach's program Ultrasmall and Ultrafast Ferrimagnetic Skyrmions Manipulated by Spins and Photons, supported by the Department of the Interior
- Professor Antoine Allanore's program A Direct Process for Wire Production from Sulfide Concentrates, supported by the DOE

MRL researchers are sponsored not only by a variety of companies but also by nearly every major federal research sponsoring agency, including the NSF, DOE, multiple Department of Defense agencies, Department of the Interior, NASA, and National Institutes of Health.

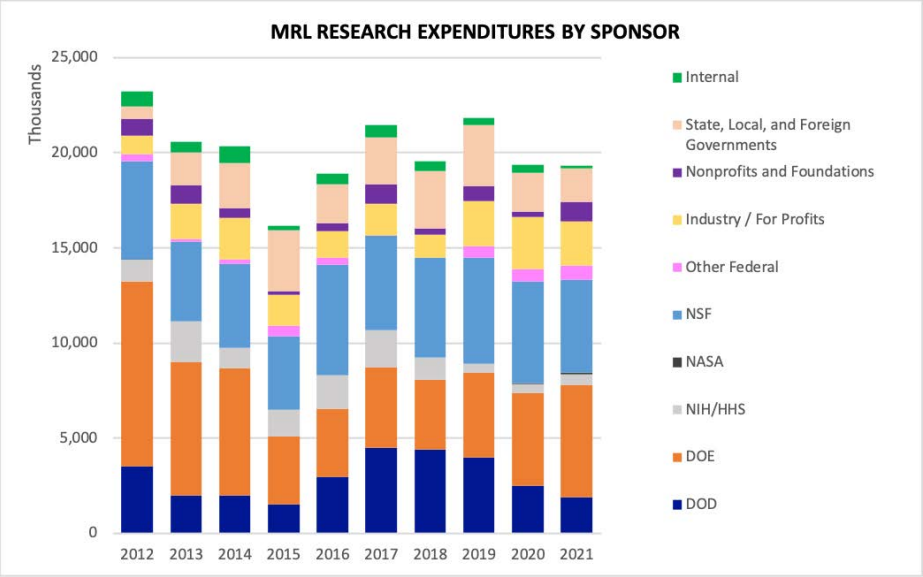


Figure 3: MRL sponsored research volume FY2012–FY2021, includes historical research expenditures for the NSF MRSEC program.

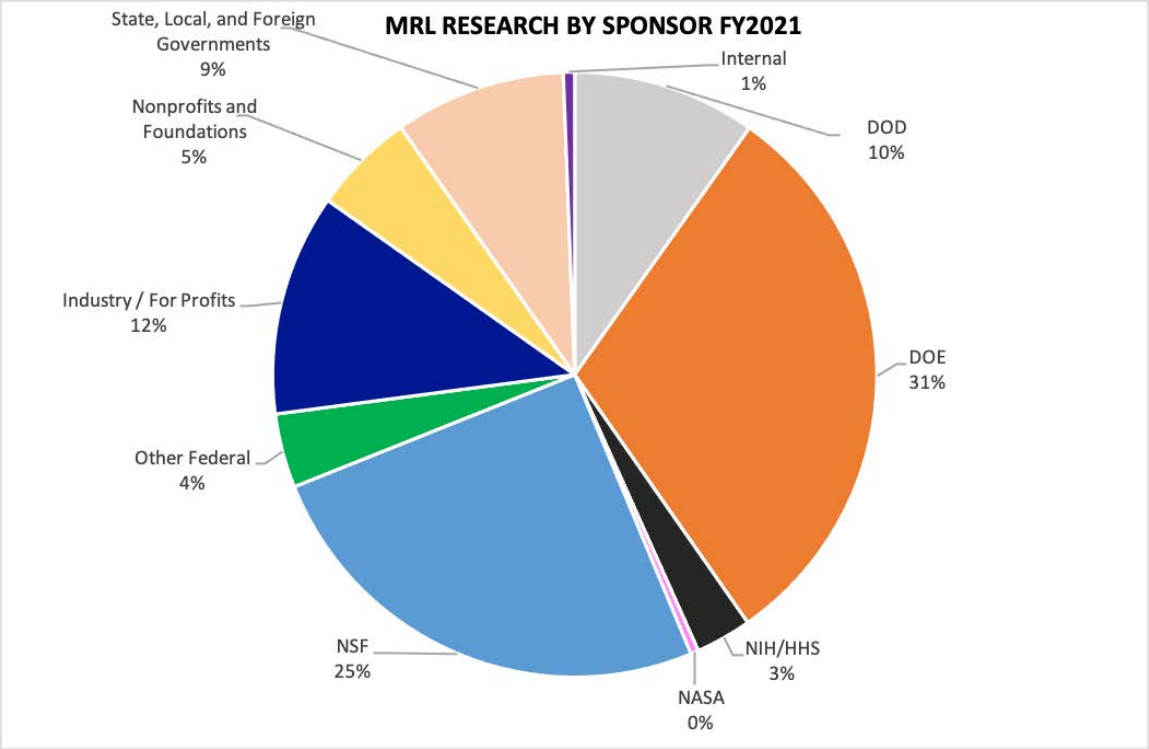


Figure 4: MRL major sponsors, FY2021 $19,323,361.

Overview and Outlook

The Covid pandemic made the past year a challenge, but it also led to new learnings that will enhance the ways in which the MRL will serve MIT's materials research community in the future.

Even though the pandemic caused a period of reduced spending as well as the delayed start of some new programs, MRL FY2021 research expenditures, $19.3 million, remained virtually unchanged compared to FY2020. A number of large, multi-investigator programs came to an end, including the Skoltech Center for Electrochemical Energy Storage and the DOE program Chemomechanics of Far-from-Equilibrium Interfaces. The SMART program for Low Energy Electronic Systems began a wind-down phase, but at the same time, a new SMART program led by Krystyn Van Vliet was begun: Critical Analysis for Manufacturing Personalized-Medicine. In addition, a number of other new multi-investigator programs began, including a DOE program led by Elsa Olivetti, Machine-Learned Processing Pathways for Solid State Electrolytes, and a new Ericsson program led by Professor Jennifer Rupp, Integration of Li Electrode Materials into Memrister Architectures for Neural Networks. Manufacturing USA Institute programs AFFOA and REMADE saw increased activity, and research efforts in condensed matter physics climbed by an additional 14% in FY2021 over FY2020, building on the 21% increase in FY2020 over FY2019. In addition, the number of PIs with active programs in the MRL increased by 16 to 79 and the MRL community developed an unprecedented high number of proposals for new research programs.

While in-person outreach activities were not possible this year, virtual events were delivered for the first time. In collaboration with the Industrial Liaison Program, the Materials Day Symposium was replaced with a virtual symposium, Advanced Materials Research for Breakthrough Technologies, which was composed of four topical symposia held over four weeks, each with faculty and student presentations and panel discussions. The average attendance for each of the four symposia was approximately 250, with 70% of participants coming from industry and with participants from over 20 countries. The MRL-MRSEC eight-week summer intern program was also held in a virtual format, with weekly group events as well as virtual interactions with MIT research groups, culminating in a well-attended virtual poster session. The nine summer interns were selected from over 170 applicants and were joined by students participating in the MRSEC partnership with Universidad Metropolitana and students from community college programs. A virtual event was also held as part of the MRSEC Women's Technology and Science Teachers Enrichment programs. As we return to in-person events, we will likely incorporate virtual elements into traditional programs as well as use virtual platforms for new modes of outreach.

This year also saw significant changes in MRL's shared experimental facilities. These facilities support approximately 1,000 unique users from across MIT each year with a suite of tools for research involving electron and probe microscopy, X-ray diffraction, and a range of techniques for materials analysis. During the pandemic, these facilities were completely closed for a period and then gradually reopened to users, with some limited restrictions still in place at the end of FY2021. During this period SEFs staff developed virtual modes for user training and support, and some of these modes have been retained as in-person interactions have become possible. Use of these facilities has now returned to pre-pandemic levels. Significant upgrades of the SEFs over the past two years have included a physical upgrade of the electron microscopy facility and installation of highly customized in situ FIB-SEM-scanning tunneling microscope, and UHV TEM equipment brought to MIT by Professor Frances Ross and a customized scanning probe near field IR nanoscopy and spectroscopy tool developed by Professor Long Ju. These tools add to a unique set of capabilities for in situ materials research enabled through customization of materials characterization equipment.

The SEFs were originally created in the 1960s and sustained over the intervening years through support by the NSF MRSEC and predecessor programs, with important supplemental support provided by the vice president for research and the deans of the Schools of Engineering and Science. The MRSEC program will come to an end in FY2022, and in anticipation of this, the SEFs became regular MIT service centers at the end of FY2021. In the coming year, the MRL leadership will work closely with a new faculty advisory committee to devise plans for future evolution of the facilities, including operational issues, development of new methods for assessment of community needs, mechanisms for acquisition and renewal of needed equipment, and further development of complementarity with other shared facilities across MIT.

The materials research community at MIT has shown resilience in the face of pandemic challenges and not only recovered from these challenges but emerged with new strengths and exciting new research programs. As we move forward this year, the MRL

will build on the experiences of the past year to better serve the materials research community as it continues to educate tomorrow's leaders and address societal challenges through innovative interdisciplinary materials research.

Carl V. Thompson
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