Center for Materials Science and Engineering

The Center for Materials Science and Engineering (CMSE), an interdepartmental center at MIT, continues to be innovative and dynamic in its promotion of interdisciplinary materials research and education. The Materials Research Science & Engineering Center (MRSEC) at MIT, established in 1994 as the core program of CMSE, is the second largest in a nationwide network of 28 MRSECs sponsored by the National Science Foundation (NSF). MIT has a large and diverse materials community with over 110 faculty members in 11 departments in the Schools of Science and Engineering. CMSE plays the critical role of bringing this diverse materials community together by encouraging and supporting collaborative research and innovative educational outreach programs.

The clear and important mission of CMSE is to encourage fundamental research and education in the science and engineering of materials for long-range applications that will address the future needs of society. The complexities of such research clearly require input from industry and the expertise of many faculty members working collaboratively in a team-based approach. Much of the research at MIT addresses intermediate-term engineering problems, often with the participation and support of industry. However, longer-range problems, especially those that require a multi-investigator approach, are often overlooked. In this environment CMSE has a special mission: to foster collaborative interdisciplinary research and education in the fundamental science of materials and in the engineering of materials for long-range applications. To accomplish this important mission, CMSE enables collaborative interdisciplinary research among MIT faculty and between MIT faculty and the researchers of other universities, industry and government laboratories.

Collaborative research is encouraged through several mechanisms: interdisciplinary research groups (IRGs), shared experimental facilities (SEFs), and outreach programs. The IRGs, described below, are composed of MIT faculty who, with their students and postdoctoral associates, investigate fundamental scientific questions and pathways to reach significant technological goals that can only be explored properly in a collaborative, multidisciplinary mode. These problems are too large in scope to be addressed by individual faculty members and their students. Collaboration is essential for materials-related science and engineering, even for individual investigators, because such research requires very sophisticated equipment. CMSE provides a mechanism for the purchase and supervision of such equipment in its SEFs. The equipment is made available to the members of the IRGs, individual MIT investigators, and researchers from other university, industrial, government, and nonprofit laboratories.

CMSE also provides seed and initiative funds to further research. While preference is given to young faculty, CMSE uses seed and initiative funds to support research that has the potential of redefining the direction of an existing IRG or leading to the creation of a completely new IRG. Seed funding provides CMSE with the flexibility necessary to initiate high-risk research.

Administration, Management, and Research

The director of CMSE reports to the vice president for research and associate provost, who reports jointly to the provost and the chancellor, the chief academic officers of MIT. Our MRSEC program is administered by a proactive and effective management team capable of responding quickly to the emerging needs of the program. Our activities are guided and supported by five committees, including a Science and Engineering External Advisory Board (SEEAB) composed of leaders of industrial and government laboratories. Of the internal committees, the most important is the Internal Advisory Committee (IAC), which advises the director about major decisions. The IAC is composed of the IRG and initiative leaders, and the faculty education and shared experimental facilities (SEF) leaders. The center is administered and staffed by an assistant director, an SEF technical manager, an education officer, a financial administrator, a facilities and safety coordinator, an administrative assistant to the director, a finance and operations assistant, and seven research staff.

In July 2002, CMSE was awarded an NSF grant of $22.2 million through the Materials Research Science and Engineering Centers program. This grant covers the funding period from September 1, 2002, through August 31, 2008. In the fall of 2005 we will host a site visit from NSF and may have the opportunity to apply for additional funding during the last two years of the award period. This past winter we submitted a noncompeting continuation proposal that described our activities during the second period (seven months) of funding of our MRSEC grant.

Interdisciplinary Research Programs

CMSE currently supports four IRGs, two initiatives, and four seed projects involving 38 principal investigators. These are summarized in the paragraphs below. In September 2003, we completed a phase-out of IRG-V (Quantum Magnetism, Correlated Electrons, and Superconductivity in Transition Metal Oxides). Although this group continued to produce high impact, internationally recognized research, our current funding level is not sufficient to maintain a five-IRG center.

Seed and initiative funding plays a critical role in the vitality of the MRSEC at MIT. The primary goals are to support research that has the potential of (1) redefining the direction of an existing IRG, (2) creating a new IRG, or (3) providing an opportunity to move quickly into new research areas. During this past funding period, we supported five seed projects and launched a new initiative entitled “Exotic States of Correlated Electrons in Single Crystals.” Due to the important contributions made by the seed effort of Y. Shao-Horn to IRG-IV, her seed was ended and she was made a full IRG-IV member. All of our current seed projects are supervised by junior faculty.

The decision to launch a new initiative was based on a unique opportunity that presented itself this past year. In 2003, Japanese researchers discovered that certain hydrated cobaltates exhibit superconductivity. The prospects of studying this new system to gain a better fundamental understanding of the mechanism of high temperature superconductivity generated a great deal of excitement in the scientific community. Only powder samples of low stability were available, however. Over the

years, CMSE has developed an extraordinary capability to grow large area, high quality single crystals of inorganic compounds within our crystal growth SEF. In a relatively short time, CMSE researchers were able to grow high quality crystals of this new material and found that they were of higher stability than powder samples. Thus, this new initiative was formed to exploit this capability through detailed theoretical and experimental investigations of single crystal cobaltates.

IRG-I: Microphotonic Materials and Structures

Microphotonic materials are rapidly emerging as one of the most promising new platforms for future optical devices and device components. Such materials allow an unprecedented level of control over the confinement and propagation of light, at dimensions that enable the design and eventual integration of a large number and variety of optical *micro* devices on a single chip. The objective of this IRG is to explore materials issues and fundamental properties of photonic crystals, to discover physical phenomena associated with photon states that have never been possible before, and to exploit this knowledge with the ultimate aim of the design, fabrication, and characterization of novel devices and components.

Participating faculty and departmental affiliations: J. D. Joannopoulos, IRG leader (Physics); E. P. Ippen, L. A. Kolodziejski, and H. I. Smith (Electrical Engineering and Computer Science); L. C. Kimerling and Y. Fink (Materials Science and Engineering); and K. A. Nelson (Chemistry).

IRG-II: Nanostructured Polymer Assemblies

Polymers and polymer nanocomposites with functional electronic, optical, and bio-interface properties are becoming increasingly important in many new technologies that exploit nanoscale related properties and effects. This IRG seeks to gain a fundamental understanding of the factors that control the way these oftentimes complex, functionally active polymer systems organize at the molecular and nanoscale levels and then use this knowledge to control and significantly enhance the performance of electronic, magnetic, biosensor, and optical devices based on these materials.

Participating faculty and departmental affiliations: A. M. Mayes, IRG leader (Materials Science and Engineering); R. E. Cohen (Chemical Engineering); M. Bawendi (Chemistry); and P. T. Hammond, C. A. Ross, M. F. Rubner, and E. L. Thomas (Materials Science and Engineering).

IRG-III: Electronic Transport in Mesoscopic Magnetic and Semiconductor Structures

Modern electronics have provided the foundation for the scientific and technological advances of the last few decades, but will soon face serious obstacles that may further limit miniaturization and development. Nanoscale elements, with properties dominated by quantum mechanics, are expected to play an important role in overcoming many of these barriers. The focus of this IRG is to explore charge and spin transport in solid-state electronic structures whose building blocks are in the nanometer size regime, in order to

understand the fundamental physical principles governing transport through and between these potentially important building blocks of future electronic devices.

Participating faculty and departmental affiliations: M. G. Bawendi IRG leader (Chemistry); R. C. Ashoori, M. A. Kastner, L. S. Levitov, and X.G. Wen (Physics); and R. J. Ram (Electrical Engineering and Computer Science).

IRG-IV: Science and Engineering of Solid State Portable Power Structures

The need for efficient portable power is extremely important in today's society and is becoming critically important to many new technologies that will impact consumer electronics and communication, health monitoring, entertainment, environmental oversight, and national security. This IRG seeks to develop the basic science and engineering of materials for solid-state electrochemical power sources, and to use this fundamental knowledge to design devices with energy and power delivery capabilities far superior to those of anything available today. The knowledge gained from fundamental materials studies is expected to have a real impact on practical advances in the battery field.

Participating faculty and departmental affiliations: G. Ceder IRG leader (Materials Science and Engineering); E. A. Fitzgerald, A. M. Mayes, D. S. Sadoway, and R. L. Smith (Materials Science and Engineering); Y. Shao-Horn (Mechanical Engineering); and M. Z. Bazant (Mathematics).

Initiative Project I: Chemically Responsive Organic Optoelectronics

The objective of this initiative is to design reproducible, high-performance organic-based transistors and sensors capable of amplified responses to chemical targets. To accomplish this objective, the group is developing new methods for the deposition of novel active and passive (protective coatings) molecules and polymers. Chemical specificity in the sensory responses is accomplished by designing materials with specific electronic structures, nanoscopic superstructures, and integration receptors. Particular emphasis is placed on receptors of biological origin, as a result of their exquisite selectivity.

Participating faculty and departmental affiliations: T. M. Swager, initiative leader, (Chemistry); V. Bulovic (Electrical Engineering and Computer Science); K. F. Jensen (Chemical Engineering); and R. J. Silbey (Chemistry).

Initiative Project II: Exotic States of Correlated Electrons in Single Crystals

The overall objective of this initiative is to discover and understand the exotic phases that arise in materials with strongly interacting electron systems. Materials of this type can exhibit unusual properties such as superconductivity, anomalously high thermopower, or infinite ground-state degeneracy. Single crystals of the newly discovered superconductive cobaltates will be synthesized and studied with the specialized techniques of neutron and synchrotron x-ray scattering and scanning tunneling microscopy (with atomic resolution).

Participating faculty and departmental affiliations: Y. Lee, initiative leader, (Physics); E. Hudson (Physics); and F. Chou (CMSE).

Seed Projects

- Electro-Mechanical Molecular Devices
  M. A. Baldo (Electrical Engineering and Computer Science)
- 3D Nanofabrication via Folding of 2D Membranes
  G. Barbastathis (Mechanical Engineering)
- Virus Engineering to Self-Assemble Hybrid Materials
  A. M. Belcher (Materials Science and Engineering)
- Functionalized Metal Nanoparticles: Building Blocks for Novel Digital Bio-Sensors
  F. Stellacci (Materials Science and Engineering)

Shared Experimental Facilities

SEFs are a critically important resource to the MRSEC program and to the MIT community, as well as to a number of outside academic and industrial organizations. A team of highly motivated professionals staff these facilities. SEFs also play a special role in the training and education of MIT students, as well as participants in the center's educational outreach programs, such as our MRET and REU participants. The center's SEFs, for example, are an integral part of many laboratory subjects taught at MIT. Currently we run four major facilities: Materials Analysis, Crystal Growth and Preparation, Electron Microscopy, and X-Ray Diffraction.

In December 2003, we added a new computer-controlled electron microscope (a JEOL 2010F TEM/STEM) to our Electron Microscopy Facility. This microscope was valued at more than $1.5 million and was purchased for $900,000 in conjunction with MIT's Institute for Soldier Nanotechnologies. Our ability to purchase this much needed, high-ticket item underscores the importance of collaborative MIT interactions (and strong long-term vendor relationships) in making expensive equipment purchases possible.

Collaboration, Outreach and Knowledge Transfer

MIT has a long-standing history of promoting collaboration with, and knowledge transfer to, industry. CMSE therefore enjoys a number of extremely effective and well-established mechanisms for knowledge and technology transfer to industry. The many excellent CMSE-supported graduate students and postdocs who leave MIT to work in industry represent an important vehicle for knowledge transfer. By emphasizing team-based, interdisciplinary research within our IRG groups, students and postdocs are trained in a mode that is critically important to meeting the complex, fast-moving challenges of industry. Indeed, the education and research programs at MIT have a proven track record of producing many industrial leaders. In addition, there is a strong entrepreneurial spirit at MIT that often leads to the development of new companies and businesses. This entrepreneurial spirit exists within CMSE as demonstrated by the fact

that in the past seven years alone, six start-up companies based on CMSE-supported research have been launched by our graduate students, postdoctoral students, and faculty. These include Cumulus Photonics (recently shut down), Clarendon Photonics, Little Optics, OmniGuide Communications, LumArray, and, just this past year, a new start-up called Luminus Devices. These various companies were founded to develop novel devices and components based on new discoveries made within our MRSEC program and, in many cases, funded exclusively through NSF.

CMSE works in concert with a number of MIT industrial programs and centers to facilitate the transfer of the fundamental knowledge generated within the program to industry. MIT's Materials Processing Center and Industrial Liaison Program, for example, work cooperatively to connect industry to the research carried out within our MRSEC program. These organizations combined have more than 200 member companies.

Our faculty report industrial collaborations and interactions with different industrial researchers, including, for example, researchers at Aerovironment, Bell Labs/Lucent, Bluefin Robotics, CibaVision, DuPont, Electrovaya, Hewlett-Packard, IBM, Intronics, JMARTechnologies, Mars Corporation, Physical Science, Raytheon, Texas Instruments, Valence Technologies, and Voltaflex. Our faculty is also very active in international collaborative activities with partners at the University of Twente (Netherlands), Istanbul Technical University (Turkey), University of Ioannina (Greece), Tokyo Institute of Technology (Japan), CNRS Bordeaux (France), National University of Singapore, Laboratorio TASC-INFM (Italy), University of Taiwan, Research Council of Canada, Toth Information Systems, Inc. (Canada), McMaster University (Canada), ETH Zurich (Switzerland), Max Planck Institute (Germany), and the École Superièure de Physique et de Chimie (France).

Education and Human Resources

Over the past five years, we have worked hard to establish a wide-reaching and diverse portfolio of educational outreach programs that are both innovative in nature and responsive to the needs of educators and students. We have now put in place a broad range of well-received programs that impact high school students and teachers, as well as undergraduate and graduate students. Our programs are managed by a full-time education officer who works closely with a faculty education program leader, the center director, and assistant director. In addition, the center's educational outreach committee consults on the direction of the education programs and the coordination of those programs with other outreach programs on campus. The committee's membership is comprised of personnel from MIT who are actively involved in educational outreach efforts. Besides involvement in CMSE's formal education activities outlined below, MRSEC-supported faculty, research scientists, and graduate students participate in outreach activities with local schools, as well as religious, community, and professional organizations. Our faculty reported that over the past grant period they devoted about 125 hours to tutoring students, making presentations at schools, youth groups, and teacher meetings, or hosting groups of students visiting MIT laboratories. The 275 students and 70 teachers who participated in these efforts are affiliated with 10 different organizations external to MIT.

Pre-College Education

Materials Research Experience for Teachers

For the past five years, CMSE has operated a successful Materials Research Experience for Teachers (MRET) program. This program brings high school and middle school teachers to the MIT campus to participate in CMSE research. The teachers spend seven weeks immersed in research during the first year of the program, then are invited to return the following summer for a flexible period of time devoted to the development of material that will transfer their research experience to their classroom teaching. The major components of the program are research, weekly discussion meetings, tours of CMSE's SEFs, and the development of classroom materials. An important goal of the program is to document the materials developed by the teachers so that they can be shared with other educators. Ten teachers participated in this program during the summer of 2003; five working on research and five creating classroom materials.

Science Teacher Enrichment Program and Women's Technology Program

CMSE will offer its Science Teacher Enrichment Program (STEP) for the third time in the summer of 2004. The goal of the program is to deepen the teachers' content knowledge in areas related to the state learning standards. It consists of a one-week, hands-on workshop entitled "Dustbusting by Design" in which the participants enhance their knowledge of the engineering design process by immersing themselves in that process. After considering the special features of a hand-held vacuum, the physics of its operation, and the properties of the materials involved, the participants design and construct motors that meet the machine's performance specifications. The final day of the program is devoted to converting the week's experience into engineering modules that address state learning standards for use in the classroom.

A companion effort to the STEP is CMSE's collaboration in the Women's Technology Program (WTP). The Department of Electrical Engineering and Computer Science administers this four-week summer residential program for high school girls from across the country, during which the participants take classes in math, 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. As a result of our early success with the STEP and its potential impact on the WTP, CMSE invited the WTP participants to join the lab portion of STEP to gain hands-on engineering experience. For the past two years, this has turned out to be an extremely successful collaboration. WTP alumni report that this motor-building lab was the most exciting part of the program. For the 2004 program, CMSE requested and received supplemental funds from the NSF to support the WTP.

Science Teacher Workshops

CMSE offers workshops that address specific content-enrichment needs to groups of science teachers. These are developed in consultation with the teachers, particularly with former participants in the MRET program and STEP.

We have also established strong working relationships and collaborations with other administrative units at MIT, including the Edgerton Center, the MIT Museum, the Materials Processing Center, MIT's Council on Primary and Secondary Education, and various MIT departments in the Schools of Science and Engineering. Interactions with these units have resulted in a number of important events, including CMSE participation in an MIT Museum program entitled "Family Adventures in Science and Technology Sundays." CMSE provided the content and materials for the FAST program held in October 2003.

Science and Engineering Program for Middle School Students

For the past 12 summers, CMSE has operated a science and engineering program for 24 seventh- and eighth-grade students from two Cambridge public schools. The objectives of the program are to familiarize the students with the field of materials science and engineering, demonstrate that science and engineering are fun and interesting, introduce students to a college environment, and expose them to some of the exciting resources at MIT. The program consists of a full summer week of hands-on and inquiry-based science and engineering classes for students from each school. Because the students are on campus from 8 am to 3 pm each day, meals are provided to participants. The center also provides bus transportation between the schools and MIT.

The program covers a wide variety of topics. Most activities take place during 90-minute periods, and some include multiple sessions. The 2003 program consisted of glassblowing, metal casting, polymer chemistry demonstrations, building an electric circuit that simulates a traffic light, building a simple motor, and a design contest. Each year the program concludes with this "shoot-the-hoop" design competition, to which the families of the program participants are invited. CMSE has developed collaborative relationships with MIT's Edgerton Center, the MIT Museum, and the Departments of Physics, Electrical Engineering and Computer Science, and Materials Science and Engineering which contribute to the development of projects and their presentation to the middle school students.

Undergraduate Education

Undergraduate Research Opportunities Program

CMSE continues to sponsor undergraduate involvement in MRSEC research through MIT's Undergraduate Research Opportunities Program (UROP). During the current funding period, 12 students (including 6 women and 2 members of an underrepresented minority group) participated in the UROP program with support from CMSE. In addition to the students paid by the MRSEC, 14 undergraduates worked on CMSE research who either were supported by other funds or received academic credit.

Summer Research Internship Program

In collaboration with MIT's Materials Processing Center, CMSE operates a Summer Research Internship Program. The program's major goals are to provide undergraduates from other institutions with an opportunity to perform cutting-edge materials research and to attract students to graduate studies in materials science and engineering. The two

centers intend to continue this collaboration. The program is open to US citizens and permanent residents who will be juniors or seniors the following fall. We receive approximately 150 applications each year, which are reviewed by a committee consisting of the CMSE director and staff from both centers. Participants are chosen from this pool on the basis of academic performance, interest statements, and faculty references. The 13 students accepted into the program for the summer of 2004 included six women and seven men.

The students are paid stipends and work full-time for ten weeks. Most of them live in a dormitory on campus. Weekly meetings are devoted to research discussions and informal seminars with guest speakers on topics such as the graduate school admissions process, research funding, and intellectual property. The interns complete the program by producing posters that report on their summer's research. The resulting poster session is held during the final week and is open to the entire MIT community. It includes posters produced by participants in CMSE's MRET program as well and serves the dual purpose of serving as a final report by the interns and teachers and informing the broader MIT materials community about the wide range of research being done under the auspices of the two centers.

Graduate Education

IRGs, initiatives, and seed projects supported by CMSE include research assistantships for graduate students. CMSE provides additional funds to support three assistantships per year for graduate students who are from underrepresented minority groups. During the coming year, CMSE will fund two graduate students in the Electrical Engineering and Computer Science and Materials Science and Engineering departments. Because the support for a minority student is supplemental to a faculty member's existing MRSEC funds, it provides additional incentive for faculty to include minority students in their research groups.

The center's SEFs play a special role in the training of MIT graduate and undergraduate students. CMSE investigators use these facilities to carry out MRSEC research, and often this requires skilled use of state-of-the-art equipment by graduate and undergraduate student researchers. SEF staff and MRSEC-affiliated faculty provide training for new users, and in some cases graduate courses are offered on a particular technique, such as electron microscopy. Educational use of SEFs is an integral part of laboratory subjects in the Department of Materials Science and Engineering's undergraduate program. Each SEF offers at least one mini-course during MIT's Independent Activities Period (IAP) in January to train students to operate the equipment and apply the latest techniques to their research problems. The following eight classes were taught by the SEF staff during January of 2004:

Characterization of Materials in a High-resolution Scanning Electron Microscope
Energy Dispersive X-ray Microanalysis in the Electron Microscope
Introduction to Surface Analysis
Introduction to Transmission Electron Microscopy
Introduction to the X-ray Diffraction Laboratory

Magnetism and Magnetic Property Measurement: Operation of the SQUID Magnetometer
Raman and FTIR Spectroscopy and Microspectroscopy at CMSE
Thermal Analysis Capability at CMSE

Colloquia

CMSE continues its colloquium series focusing on MRSEC research. The objectives of the colloquium series are to highlight the interdisciplinary nature of CMSE's research; to provide an opportunity for faculty, research staff, and students from different disciplines to meet on a regular basis to discuss their approaches to materials problems; and to inform the greater MIT community about materials research.

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Director
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More information about the Center for Materials Science and Engineering can be found online at http://web.mit.edu/cmse/www/.