Center for Materials Science and Engineering

The Materials Research Science and Engineering Center (MRSEC) at MIT, funded by the National Science Foundation (NSF), was established in 1994 as the core program of the Center for Materials Science and Engineering (CMSE). In September 2008, NSF awarded CMSE a renewed six-year $19.2 million MRSEC center grant to fund CMSE's research and educational outreach programs as well as its shared experimental facilities from September 2008 to August 2014. This award was the culmination of an extensive two-year internal and external review process and proposal preparation at CMSE headquarters that enabled CMSE to compete with over 100 other national institutions to win one of 14 NSF MRSEC center awards for this six-year period. During FY2014, CMSE competed in a new six-year MRSEC center grant renewal for the 2014–2020 time period. This latest competition also involved a two-year internal and external review process and a proposal submission by CMSE headquarters. The results will be announced soon.

CMSE promotes and facilitates interdisciplinary research and education in the science and engineering of materials. MIT has an exceptionally strong and broad effort in materials science and engineering involving more than 180 faculty members in 14 different departments in the School of Engineering and the School of Science. CMSE plays the critical role of bringing this diverse materials community together by encouraging and supporting collaborative research and innovative educational outreach programs and by providing state-of-the-art shared experimental facilities (SEFs). The clear and important mission of CMSE is to enable—through interdisciplinary fundamental research, innovative educational outreach programs, and directed knowledge transfer—the development and understanding of new materials, structures, and theories that can impact the current and future needs of society. The complexities of such research clearly require input from industry and the expertise of many faculty working collaboratively in a team-based approach. To accomplish this important mission, CMSE enables collaborative, interdisciplinary research among MIT faculty and among MIT faculty and researchers from other universities, industry, and government laboratories.

CMSE promotes collaborative research through several mechanisms: interdisciplinary research groups (IRGs), seed and initiative projects, SEFs, and outreach programs. While seed funding 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, transformative research. Our research programs typically support a total of 30 to 40 faculty members from 10 or more departments. During the first five and a half years of our 2008–2014 MRSEC award, researchers published results in 419 papers and were awarded 46 patents related to their MRSEC research, with 81 more patents pending.

Our SEFs are used by numerous research groups from MIT as well as by outside academic and industrial communities. During the March 2013 to February 2014 period, 1,267 people used our SEFs, including 991 students and postdocs of MIT faculty in 26 academic departments, labs, and centers; 77 students and staff of faculty from 16 outside academic/research institutions; 175 students from MIT lab subjects; and 24 staff of senior-level industrial managers.

Our educational outreach programs encompass a broad range of activities and age levels, with participation from K–12 students and teachers and undergraduates from other institutions. During the summer of 2013, 117 people participated in our various core programs with support from CMSE-funded faculty, graduate students, and postdocs. CMSE MRSEC faculty also devoted many hours to tutoring students, making presentations to students and teachers, supervising high school students in their labs, and hosting groups of students visiting CMSE labs. More than 850 people attended workshops and public events in which CMSE took part.

Interdisciplinary Research Programs and Scientific Accomplishments

The MRSEC grant supports three IRGs, two initiative projects, and seed projects involving 36 principal investigators (PIs). The research results for all groups funded in FY2014 are reported below.

IRG-I: Design of Nanomaterials for Electrochemical Energy Storage and Conversion

The objective of this IRG is, on the one hand, to use electrochemistry to accurately determine how thermodynamics, phase stability, and kinetics are modified at the nanoscale, and, on the other hand, to apply that knowledge to engineer materials with high-energy, high-power Li storage capabilities, and to design nanocatalysts with superior oxygen reduction reaction activity and reduced noble metal content. The supply of sustainable energy is arguably the most important scientific and technological challenge in the 21st century. Meeting this challenge will require not only increased energy efficiency but also new energy storage platforms to displace existing carbon-based fuels with carbon-neutral energy such as solar energy. Electrochemical devices such as Li batteries and fuel cells that operate on hydrogen produced from solar energy are promising technologies to buffer the supply and demand of energy, particularly for portable power and hybrid propulsion in transportation. Meeting the demands of these applications requires new ideas to design materials with tailored reactivity toward lithium for Li batteries and catalysts with markedly higher activity towards oxygen reduction reactions in fuel cells.

Faculty participants and department affiliations: G. Ceder, co-leader (Materials Science and Engineering [DMSE]); Y. Shao-Horn, co-leader (Mechanical Engineering); A. Belcher (DMSE and Biological Engineering); K. Hamad-Schifferli (Mechanical Engineering and Biological Engineering); D. Nocera (Chemistry); T. Van Voorhis (Chemistry); and C. Thompson (DMSE).

FY2014 IRG-1 Results

IRG-I members have been investigating important details concerning the chemistry of high-energy density battery systems based on Li-O2 and Na-O2. In the case of Li-O2 batteries, it was found that DMSO, an electrolyte solvent used to promote reversible formation of Li2O2 (the main battery reaction product), can eventually react to form undesirable amounts of LiOH and that the presence of KO2 enhances the reactivity of Li2O2 with DMSO. These results emphasize the importance of using model systems to understand how different components of discharge product chemistry influence the practical operation of Li-O2 batteries. For the Na-O2 battery system, first-principles calculations were used to investigate the thermodynamic stability of the three potential discharge products of this system: Na2O, Na2O2, and Na-O2. Of particular interest was their relative stability at the nanoscale, where it was found that stabilization of NaOv was favored over Na2O2. These findings are expected to direct efforts toward understanding and controlling the formation of desired Na-O compounds in battery operation. In an exciting new development, IRG-I researchers have utilized biology to synthesize transition metal oxide nanowires for use as cathode materials in Li-O2 batteries. A virus templating approach was used to create nanowires of varying composition and surface area that, when decorated with conductive Ni nanoparticles, exhibited lower charging potentials and enhanced cycle life. It is expected that this engineering method can be easily adapted to nanowires based on electrodes with a diverse combination of materials. In another direction, theoretical calculations were used to compute lower bounds on the electrochemical overpotentials of the oxygen evolution reaction occurring on a variety of transition metal oxide surfaces. Understanding this reaction is important for the development of efficient hydrogen fuel cells. A key finding was that the rate of oxygen evolution does not depend on the particular mechanism of the basic reaction (2H2O → 2H2 + O2), making it possible to predict overpotentials without concern regarding the precise mechanism in play. Finally, a number of organic electrode materials were screened for electrochemical energy storage device applications. Polycyclic aromatic hydrocarbons were mixed in a functionalized carbon nanotube (CNT) matrix to explore their use as high-energy and high-power positive electrodes for pseudocapacitor applications. Suitably designed nanostructured pyrene derivatives, in combination with oxidized CNTs, were found to exhibit energy densities of approximately 350 Wh/kg electrode at power densities of approximately 10 kW/kg electrode for more than 10,000 cycles.

IRG-II: Mechanomutable Heteronanomaterials

This IRG seeks to develop a new class of “mechanomutable heteronanomaterials,” which are defined as possessing spatially localized and controlled nanoscale units of different types of materials that change their mechanical properties reversibly in response to an external stimulus. The use of heteronanostructures provides many exciting possibilities for mechanomutable materials design that have not yet been realized, in particular high-spatial-resolution interactions with nanoscale objects and unique and amplified mechanical robustness. For this reason, IRG-II explores the possibility of utilizing these materials as high-throughput, high-spatial-sensitivity tunable sensors (e.g., for cells, proteins, localized impacts, and pressure in liquids).

Faculty participants and department affiliations: R. Cohen, co-leader (Chemical Engineering); C. Ortiz, co-leader (DMSE); M. Boyce (Mechanical Engineering); M. Buehler (Civil and Environmental Engineering); P. Hammond (Chemical Engineering); K. Van Vliet (DMSE); and A. Balazs (University of Pittsburgh).

FY2014 IRG-II Results

IRG-II researchers continued investigations of a new mechanomutable system composed of surface-anchored hollow nanotubes of polyelectrolyte multilayers. A novel coarse-grain model developed to represent large-scale 3D arrays of the multilayer nanotubes exploits the computational efficiency of full atomistic algorithms. Using this model, it was found that intertube contacts result in the amplification of effective normal and lateral resistance or stiffness. This suggests that a range of mechanical responses can be engineered by tailoring different geometrical parameters (e.g., tube height, cross section, spacing). As an indirect offshoot of this work, a new multilayer system with anti-frost capabilities has been developed that appears promising for applications ranging from frost-resistant freezer doors to frost-resistant optics. This new coating system exhibits the unusual property of "zwitter-wettability"—the ability to appear both hydrophobic and hydrophilic at the same time. The basic mechanism of frost prevention is related to the coating's unique ability to adsorb molecular water in a nonfreezing state. In the area of mechanomutable self-oscillating polymer gels, IRG-II researchers have made the remarkable discovery that oscillations in volume and color can be induced independently in resting gels by both mechanical and temperature triggers. When an array of gel disks is formed, a mechanical trigger of one gel disk is not transmitted to the others. However, when temperature is increased, the other gel disks are triggered to also oscillate in color and volume. The IRG-II group has also reported on the development of a mechanomutable supramolecular hydrogel composed of an electrochemically active ferrocenophane polymer and β-cyclodextrin modified single wall carbon nanotubes whose mechanical properties can be electrochemically switched with relatively fast cycle times. These new mechanomutable systems open the door to the design of tailorable coatings and patterned arrays with applications in both micro- and nanoscale sensing devices.

IRG-III: Multimaterial Multifunctional Nano-Structured Fibers

This IRG explores the materials science, design, fabrication, characterization, and potential identification of novel physical phenomena of a truly unique class of fiber materials systems that are composed of conductors, insulators, glassy semiconductors, and especially crystalline semiconductors with more than 10 nanometer feature sizes. These fibers, while comprising all of the essential crystalline semiconductor device attributes, are processed using conventional fiber draw processing approaches, thus yielding kilometers of fiber structures with engineered electronic, optical, thermal, and acoustic properties and exploiting photonic bandgap phenomena wherever needed.

Faculty participants and department affiliations: Y. Fink, co-leader (DMSE); M. Soljacic, co-leader (Physics); J. Joannopoulos (Physics); S. Johnson (Mathematics); E. Ippen (Electrical Engineering and Computer Science [EECS]); A. Abouraddy (University of Central Florida); and P. Anikeeva (DMSE).

FY2014 IRG-III Results

IRG-III researchers have developed a new fiber-based particle fabrication methodology that can be used, for the first time, to prepare crystalline silicon spheres with nanometer dimensions. Utilizing a capillary breakup process in conjunction with axial thermal gradients and a controlled feed speed, they were able to systematically control sphere diameter as well as produce multiple-core fibers. In the latter case, a multiple-core breakup process was used to fabricate functional silicon devices regularly spaced within a silica fiber, including a string of in-silica-fiber silicon PN junctions exhibiting rectifying behavior. This exciting development is expected to enable the fiber weaving of ultra-sensitive photodetecting and solar-energy-harvesting fabrics. The group also reported on the use of in-fiber fluid instabilities to fabricate nanoparticles (with dimensions as small as 50 nm) from a wide range of different polymeric materials. This particle fabrication strategy is amenable to the mass production of biocompatible polymer nanoparticles containing different biologically active cargos, thereby enabling broad applications in cancer treatment, immunology, and vaccines. The unique fiber technology developed by this group also has great potential in the area of neural science. For example, the group reports the demonstration of a novel class of fiber neural probes that can perform simultaneous in vivo optogenetic stimulation and neural recording and deliver pharmacological compounds through hollow channels created in core or shell layers. In addition, a two-step thermal drawing process was used to fabricate high-density electrode arrays, consisting of metal electrodes and a polymer cladding, that were used to record spontaneous single-neuron activity in a mouse. The ability to produce high-quality nanoparticles using fluid instabilities in a fiber drawing process has motivated the investigation of a new type of nanoparticle-based transparent display. Based on the wavelength-selective resonant scattering properties of nanoparticles, the group developed a low-cost, wide-viewing-angle transparent display that is readily scalable to large sizes.

Initiative-I: High Def Nanomaterials: New Routes to 3D Hierarchical Nanostructured Materials and Devices

Long-Term Research Goals and Intellectual Focus

HD nanomaterials refer to a new class of 3D bulk material elements that can be tailored at the sub-nanometer scale by combining solution-based layer-by-layer (LBL) processing and related techniques (Cohen-Rubner) with the bulk 3D nanoporous carbon scaffolds recently developed and demonstrated as microfluidic elements (Toner-Wardle). Although the applications for this work are manifold, this initiative focuses on developing a fundamental understanding of LBL assembly onto the 3D nanoporous elements, extending the recent space-constrained LBL of Cohen-Rubner to smaller spaces (accessible via aqueous routes) approaching single-nanometer dimensions while simultaneously extending it from planar facing channels to 3D bulk nanoscale features (i.e., for an equivalent volume of channel). In essence, the LBL assembly process will now occur on 3D surfaces with 5–20 times smaller constraints and more than 2,000% higher surface areas. Biofunctionalized nanoelectromechanical systems (BioNEMS) devices for bioparticle isolation will directly benefit from the surface modification provided by LBL, as it will allow a myriad of new functionalities for the devices to be targeted, moving away from simply functionalizing to truly tailoring and enabling new types of bioparticle manipulation. For example, a targeted device effort will seek to demonstrate LBL-enabled bioparticle capture and manipulation focusing on the HIV virus, approximately 100 nm in size. This capability is currently inaccessible by state-of-the-art nano/microelectromechanical systems platforms. Success in such a device will lead to much broader investigations of nanoparticle-based information about disease processes in the body in future work, including investigations of before-untargeted information packets in fluids (e.g., blood contains nanometer-scale exosomes in small quantities that could be used to track disease evolution and treatment effectiveness). This initiative's work on LBL assembly into bulk nanoporous elements will impact numerous other fields such as filtration, titration, and nanostructured anodes/cathodes.

The ability to tailor interfaces has led to many of the technological advances in materials in recent decades across all domains and is particularly relevant when considering nanoscale effects. Biomedical research has particularly benefited from advances in surface chemistry and surface manipulation, enabling a large number of applications from controllable release/adsorption of proteins to affinity chromatography. Layer-by-layer deposition has emerged as a facile and flexible route toward layered molecular assembly, unlocking great potential particularly on films and surfaces. Extending LBL techniques to bulk materials with controlled nanoscale morphology is largely an unexplored area, and it is pursued here via a new route based on microfluidics for achieving 3D LBL assembly through solution processing into nanoporous scaffolds.

Faculty participants and department affiliations: B. Wardle (Aeronautics and Astronautics), R. Cohen (Chemical Engineering), M. Rubner (DMSE), and M. Toner (Health Sciences and Technology).

FY2014 Initiative-I Results

Initiative-I researchers are developing a new platform technology composed of functionally active, patterned nanoporous scaffolds created from carbon nanotubes and contained within microfluidic devices. Modeling and device design efforts have demonstrated that it is possible to controllably functionalize the nanotube arrays with either annular nanoscale coatings or fully penetrated coatings, both of which offer unique opportunities for bioparticle capture and detection. Along these lines, a new functionalization protocol was developed for the capture and detection of prostate-specific antigen (PSA) with the ability to detect PSA in the very dilute and clinically relevant concentration range of 10 ng/mL to 0.1 ng/mL. This new chemistry was fully implemented in a working microfluidic device, moving such devices closer to technologically relevant applications.

Initiative-II: Quantum Optoelectronics and Spintronics with Topological Insulator Nanoscale Devices

The aim of this initiative is the development of topological insulator (TI) materials suitable for electronic, magnetic, and optical devices. TIs represent a novel paradigm in condensed matter physics, where materials are classified according to the topological order of their band structure. TI devices are expected to allow the investigation of a variety of new quantum phases and to open a broad range of spin-based functionalities. The studies carried out as part of this initiative are focused on the development of TI devices fabricated from thin films and the development of sensitive techniques for spin mapping of TI materials. The ideal TI would be an insulator in bulk and support electronic transport only through its topological surface states. At present, TI materials such as Bi2Se3 are plagued by a finite carrier density in the bulk. The presence of these carriers limits the applicability of TI devices and hinders the study of surface effects. Growth of TI thin films in high vacuum conditions is a promising approach to addressing these problems. It is also a particularly useful strategy for device fabrication since it offers fine control over geometry and composition and allows the growth of heterostructures.

Faculty participants and department affiliations: P. Jarillo-Herrero (Physics), N. Gedik (Physics), and J. Moodera (Francis Bitter Magnet Laboratory).

FY2014 Initiative-II Results

Initiative-II researchers have successfully fabricated TI-based nanodevices incorporating simultaneous top and bottom electrostatic gates. Using these devices, they were able to demonstrate that both surface states could be independently tuned through a resistance peak and that electric fields penetrate through the bulk of the TI crystal. The group also reports that a small electric field can break the mirror symmetry responsible for the metallic character of the surface states of a TI and convert the surface states to an insulating state. A device based on this effect effectively works as a topological insulator transistor switch, enabling the charge and spin transport at the surface of TIs to be controlled with a high on/off ratio, fast operational speed, and low energy consumption. This new approach may lead to the development of topological crystalline insulator–based electronic and spintronic technology beyond the current complementary metal-oxide-semiconductor technology. Initiative-II researchers have further succeeded in converting the TI surface states to an insulating state by coupling the TI to a ferromagnetic insulator. The intrinsic magnetic domains of the ferromagnetic insulator, in turn, produce novel conducting channels on the surface of the TI exactly at domain boundaries. These topological conducting states have long been theoretically proposed but only now observed.

FY2014 Seed Research

Seeds Completed in 2013

Seed-I: Bioinspired Environment-Responsive Ligand-Coated Nanoparticles

The goals of this seed project were to gain a theoretical understanding of the interactions between ligand-coated gold nanoparticles (NPs) and cell membranes and to develop design principles for using such NPs in biomedical applications ranging from targeted drug delivery to bioimaging. These NPs consist of a gold core and an amphiphilic grafted oligomer layer such that the surface properties of the NP are determined primarily by the choice of ligands grafted to the surface. Importantly, the ability of the flexible ligands to fluctuate through available free volume allows the NP's surface to respond to changes in the surrounding microenvironment, yielding environmentally responsive properties that allow the NPs to match their amphiphilic surfaces to similarly amphiphilic lipid bilayers. Thanks to this seed funding, a new path by which these NPs can interact with membranes and fuse with them has been discovered. This observation was only previously reported experimentally. These findings are of utmost importance and very timely, as similar types of NPs are already being used in phase 2 clinical trials. In addition, these results lay the foundation for a new field of drug delivery and the production of synthetic materials that can behave as biological counterparts. They not only fuse with membranes but also mediate liposome-membrane interactions in a manner that is similar to how fusion proteins present in neurons (and in most cells). Results showed that these NPs can penetrate into the bilayer center and obtain a transmembrane-protein-like conformation that maximizes contact between hydrophobic lipid tails and hydrophobic surface components on the NP. Building on the results of this "globally responsive" model, a novel implicit bilayer/solvent model was developed to calculate the free energy change associated with translocating a ligand-coated NP from solution to the previously identified transmembrane configuration. This work represents the first theoretical study of synthetic NPs capable of mimicking transmembrane proteins, such as fusion proteins, while being fully water soluble and biocompatible. The physical insight gained from this work will lead to the development of a new generation of biomimetic NPs useful not only for drug delivery and biomedical applications but also for serving as a platform for understanding interactions at biological interfaces. The seed funds provided by MRSEC for this proposal allowed the PI to open a completely new field in the area of nanoparticle-membrane interactions, and the results led to him publishing several papers in high-impact journals (e.g., *Nano Letters*). The results have also paved the way for other sources of funding to continue the project. PI: A. Alexander-Katz (DMSE).

Seed-II: Ordered Microporous Electrodes for High-Power Sustainable Li-ion Batteries

This seed project sought to build novel organic electrodes for Li+ batteries from microporous covalent organic frameworks. Owing to their innate porosity, which should allow efficient Li+-ion intercalation, these materials are expected to enhance the poor power performance of organic electrodes, thereby providing an economical alternative to current battery electrodes. During the course of the research supported by MRSEC, critical tests of some of the initial hypotheses were carried out, and the results confirmed that these materials show promise for Li-ion batteries. The first few electrochemical experiments on metal-organic frameworks demonstrated that electron transfer occurs between the electrode and the organic ligands. Although investigations are continuing, the results of the MRSEC-supported research were included in three different proposals prepared by the PI: one as part of a larger Department of Energy (DOE)–funded Excitonics Energy Frontier Research Center (EFRC) effort, an independent proposal for the Office of Naval Research Young Investigator Program, and a proposal for the NSF Faculty Early Career Development (CAREER) Program. Therefore, the support of MRSEC proved essential in allowing the PI to seek stable funding from various government agencies. PI: M. Dincă (Chemistry).

Seed-III: Engineering and Patterning Multiscale Nanostructures with Synthetic Biology

Amyloids are aggregates of proteins or peptides with cross-beta structure and fibrillar morphology that assemble via a rate-limiting nucleation step followed by fibril extension. Self-assembly of amyloid nanowires is based on amino-acid interactions between individual subunits that are programmable via the underlying genetic code. The goal of this project was to engineer curli fibers, which are surface-expressed functional amyloids found in *Escherichia coli*, and explore how genetic changes to the curli subunit, CsgA, affect its functional, chemical, and mechanical properties. Individual curli fibrils are approximately 3–4 nm in diameter, can grow to many microns in length, and can laterally associate to form larger bundles. The CMSE seed grant made it possible to explore an exciting new direction of research at the intersection of synthetic biology and materials science that would otherwise be challenging to pursue. Natural biological systems, such as biofilms and tissues, implement dynamic regulatory programs to assemble complex multiscale materials made up of living and nonliving components. Such systems provide inspiration for the design of composite systems that integrate biotic and abiotic materials via hierarchical self-assembly. To explore hybrid materials and systems composed of both living and nonliving components, synthetic bacterial biofilms were designed that can synthesize and pattern self-assembled functional materials across multiple-length scales. In addition, these systems can interact with living as well as nonliving materials. This platform enables the creation of "living functional materials" for next-generation applications such as autonomous biomanufacturing, self-healing materials, and environmentally responsive materials. Results of the work have been published online in *Nature Materials*. The CMSE seed grant also provided sufficient data to secure support from the Army Research Office and the Office of Naval Research for this work. PI: T. Lu (EECS).

Seed-IV: Atomic Layer Deposition for the Design of Novel Catalytic Materials

This project sought to understand the synthesis and catalytic properties of isolated Lewis acid sites inside hydrophobic zeolites that provide high water tolerance. The production of these advanced catalytic materials with molecular control over the placement of single-component and multicomponent active sites allows for highly selective chemical transformations. During this project, it was demonstrated that the use of tin-containing zeolites with the beta topology with borate salts promotes the selective epimerization of aldoses in aqueous media. The reaction mechanism investigated, using 13C-labeled sugars and nuclear magnetic resonance (NMR), proceeds by way of a 1,2 carbon shift wherein a bond between C-1 and C-3 is formed, with C-1 moving to the C-2 position with an inverted configuration. Prior to this discovery, only one other inorganic catalytic system was known to promote the epimerization reaction. The results were published in *Nature Communications*. Seed funding enabled the use of various characterization instruments, including NMR, transmission electron microscopy, X-ray photoelectron spectroscopy, and Raman spectroscopy, that were critical to elucidate the reaction mechanism and to extract valuable structure-reactivity relationships. This project led to the PI's first "high-profile" publication at MIT and paved the way for other sources of funding to continue the project. PI: Y. Roman (Chemical Engineering).

Seed-V: Electrical-field Controlled Bio-membranes for Efficient Water Desalination

Surfactants have remarkable properties and behaviors that could potentially be used to improve desalination technology, especially in regard to lowering energy costs and reducing fouling. Lipids are biosurfactants and can form a bilayer membrane, which could serve as a reverse osmosis membrane if small nanopores can be opened and closed with an electric field. This approach is potentially less energy consuming than conventional reverse osmosis due to higher permeability. Another approach to desalination uses phase change processes wherein the inclusion of surfactants in evaporating water can promote ebullition, thereby lowering the temperature requirements, saving energy, and preventing high-temperature fouling. Seed funding was used to pursue these two approaches to desalination. MRSEC seed funding made it possible to carry out a completely new research direction in the PI's group that involved the use of surfactants to improve desalination technologies. This highly exploratory effort focused on the creation and fundamental understanding needed to advance tunable biomembranes for reverse osmosis. Meanwhile, the research support led to a very interesting discovery of using surfactants to dynamically tune boiling behavior. The results of this work have some interesting implications for desalination systems, as well as other problems related to energy conversion and thermal management. PI: E. Wang (Mechanical Engineering).

Multi-faculty Seed: Soft-Matter Hierarchical Assemblies for Directed Energy Flows

This project sought to develop antenna structures that are hierarchically organized to maximize energy flows in the form of electron-hole pairs (excitons) and could eventually be used to direct electrons and/or holes. The molecular control of the transport of excitons can revolutionize fields in which photon harvesting and energy conversion are key elements. In order to achieve the creation of hierarchical supramolecular assemblies with enhanced transport properties, it is necessary to control the order of the chromophores, which was proposed by templating them in block copolymers. Functional molecules such as organic chromophores, proteins, and DNA have complex structures whose utility would be enhanced if they could be processed into ordered materials with controlled morphologies. These structures often appear under aqueous conditions due to the unique interactions possible there (such as hydrophobic interactions, hydrogen bonding, and Coulombic forces), and 39 water-compatible templates and processing methods are necessary to achieve this goal. To this end, the group developed a model block copolymer, poly(oligoethylene glycol methyl ether methacrylate)-poly(2-vinylpyridine) (POEGMA-P2VP); this double hydrophilic block copolymer consists of one uncharged block and one weak polycation. When positively charged, P2VP can interact with and pattern negatively charged functional molecules (e.g., dyes and proteins); tuning its degree of protonation can tune the strength of this attraction and, thus, the resultant morphologies and activities of functional blend films. This diblock also displays interesting self-assembly when blended only with acids; it is disordered in the acid-free case but undergoes a disorder-order transition as the P2VP protonation level increases. After casting, the films can be effectively solvent annealed with the polar organic solvents (such as DMSO or DMF) typically used by polymer scientists or aqueous solvents of varying pH. The latter can dynamically change the protonation state during annealing and are compatible with proteins and other delicate hydrophilic molecules. A paper describing the acid-base self-assembly process is currently under review, and follow-up papers focusing on protein and J-aggregate templating are being developed. Faculty participants and department affiliations: A. Alexander-Katz, co-leader (DMSE); B. Olsen, co-leader (Chemical Engineering); C. Ross (DMSE); T. Swager (Chemistry); and M. Baldo (EECS).

Seeds Initiated in Fall 2013

Seed 1: Simple Engineered Biological Motifs for Complex Hydrogel Function

The objective of this research is to identify, engineer, and exploit the interplay of simple molecular motifs that are diagnostic for complex biological hydrogels. Three basic molecular motifs that are found in the molecular building blocks of complex hydrogels—conserved repeat domains, dynamic crosslinkers, and glycosylation—will be explored. Initial work will focus on the synthesis of new polymeric materials that are designed to reconstitute each of these three design motifs independently. A key goal is to refine these materials and then combine them in novel ways to reproduce, and surpass, the sophisticated materials properties found in complex biological hydrogels. It is anticipated that this approach will help to answer new questions about the mechanisms governing biological hydrogel function. In addition, it will allow control of hydrogel function in unprecedented ways, with potentially wide engineering implications including the design of self-healing filtration systems for water and food purification, new antimicrobial coatings for implants, and cartilage substitutes with high durability and lubrication capacity. Natural hydrogels also have filtration properties unmatched by synthetic chromatography systems. The well-defined building blocks from the nuclear pore hydrogel (repeats composed of hydrophobic and hydrophilic domains) will be used to identify the parameters that govern selectivity and to engineer synthetic hydrogels with tailored selectivity. PI: K. Ribbeck (Biological Engineering)

Seed 2: Nanoionics at the Interface: Charge, Phonon, and Spin Transport

This research seeks to discover the coupling mechanisms between oxygen defects and the transport of phonons, spin, and charge at the interfaces of metal oxides, with important implications for energy and information technologies. The initial research will focus on control of resistive switching in redox-based memories, magnetoelectric coupling, and thermal conductivity control through in situ defect control and making vertical nanostructures for efficient fuel cells. This work has already demonstrated that thermal conductivity can be impacted by varying the concentration of oxygen vacancies and reduced cations in Pr0.1Ce0.9O2-δ thin films prepared by pulsed laser deposition. The oxygen vacancy concentration was controlled by altering the oxygen partial pressure between 1Å~10-4 and 1 atm at 650°C. Corresponding changes in oxygen nonstoichiometry (δ) are monitored by detecting the lattice parameters of the films with high-resolution X-ray diffraction, while the thermal properties are characterized by time-domain thermoreflectance measurements. The films were shown to exhibit variations in oxygen vacancy content and in the Pr3+/Pr4+ ratio corresponding to changes in δ from 0.0027 to 0.0364, leading to a reduction in thermal conductivity (k) from 6.62±0.61 to 3.82±0.51 W/m-K. These values agree well with those predicted by the Callaway and von Baeyer model for thermal conductivity with the presence of point imperfections. The results, which were published in *Applied Physics Letters*, demonstrate the capability of controlling thermal conductivity via control of anion and cation defect concentrations in a given reducible oxide. PI: B. Yildiz (Nuclear Science and Engineering).

Seed 3: Two-Dimensional Barrier Materials for Controlling Molecular Transport and Adsorption

Materials composed of a single atomic or single unit cell layer are an emerging class of two-dimensional structures with unique properties for manipulating molecular transport and surface adsorption. The goal of this work is to engineer the unique properties of these extreme materials to demonstrate new concepts in the manipulation and control of molecular transport and adsorption as well as the generation of new structural motifs through their self-assembly. By combining advances in the understanding of mass transport and adsorption through and on these materials with new self-assembled structures, this research will enable the foundation for new types of chemical and biological sensors, separation and purification devices for gases and liquids, passivation layers for materials, electronic circuit elements, and catalytic substrates with unprecedented performance. PI: M. Strano (Chemistry)

Shared Experimental Facilities

Our SEFs are a critically important resource to our MRSEC program and to the MIT community, as well as a number of outside academic and industrial organizations. Currently we run five major facilities, Materials Analysis, Crystal Growth and Preparation, Electron Microscopy, X-ray Diffraction, and Nano Materials, staffed by a team of highly motivated professionals. During the year ending February 2014, 1,267 different individuals utilized our facilities.

Beyond the special role our SEFs play in the training and education of MIT students, they are also an important part of CMSE's education programs. Undergraduates participating in the summer internship programs (Research Experiences for Undergraduates [REU] and Community College Students) are trained to use equipment in the SEFs to conduct their research. Teachers in the Research Experience for Teachers (RET) program spend one morning each week learning about the capabilities and research applications of the equipment in the SEFs. Some of them are also trained to use the instruments for their research projects. Finally, the SEFs are included in visits to CMSE by various groups of middle and high school students.

Some of the key activities carried out during the past year are detailed below.

The SEF staff has been an important element of many of our educational outreach programs and enthusiastically embraces this role. For example, our staff play a special role in the training of MIT graduate and undergraduate students and our summer educational outreach participants. During this academic year, 175 undergraduate students used the facilities as part of their laboratory subjects. Lab subjects included courses in the Departments of Materials Science and Engineering and Earth, Atmospheric, and Planetary Sciences.

SEF staff members offered a number of mini-courses during MIT's 2014 Independent Activities Period (IAP) to train students to operate SEF equipment and apply the latest techniques to their research problems. In January of 2014, a total of 21 students and postdoctoral associates attended courses taught by the SEF staff. Because of the unusually harsh weather conditions in the Boston area during IAP, only four of the six scheduled courses were held.

After an extensive analysis of the status of CMSE's shared facilities, a critical need was identified to update the capabilities of the electron microscopy facility. To accomplish this goal, a rigorous vendor competition was held to obtain the best new state-of-the-art instruments for this facility. The purpose of the competition was to significantly increase the capability and performance of the instruments provided to the facility's users. In this process, two very popular but older instruments, a 30-year-old JEOL 200CX transmission electron microscope (TEM) and an 18-year-old JEOL 6320F high-resolution scanning electron microscope, were replaced with an FEI Tecnai G2 Spirit TWIN TEM and a Zeiss Merlin scanning electron microscope. Both instruments are now up and running to serve the materials community.

Materials Research Facilities Network

In FY2014, students and faculty from around the United States and the world came to MIT through an NSF Materials Research Facilities Network (MRFN) supplement to our MRSEC grant. This MRFN supplement enables students and faculty who do not have access to instruments such as those available at our SEFs to visit MIT so that they can learn about and use these types of instruments. A graduate student researcher from the University of Campinas (São Paulo, Brazil) used MRFN funds to travel to the United States to access the SEFs and foster a center-driven international collaboration with MRSEC researchers. In addition, Dr. Elham Fini, an assistant professor of civil engineering at North Carolina A&T State University (NCA&T), visited MIT with several students from her university. Dr. Fini was a participant in the 2011 leadership development institute conducted by the Quality Education for Minorities Network with support from NSF, and she subsequently established a research affiliate appointment with CMSE. Dr. Fini submitted a proposal to MRSEC ("Investigating Phase Structure and Crystallization Pattern of Bio-Modified Rubber Asphalt Containing Nano-Clay") and received an MRFN supplement award. Also, several groups from Puerto Rico are scheduled to come to CMSE during the summer of 2014 through this program.

Launching of a New Shared Experimental Facility

A $1,837,421 NSF American Recovery and Reinvestment Act grant to renovate 2,900 square feet of laboratory space in Building 13 has led to the creation of a new, energy-focused shared experimental facility. The research tools housed inside the facility support several large interdisciplinary programs, including the Eni Solar Frontiers Center at MIT, the MIT Solar Revolutions Center, the Excitonics EFRC, the MIT Solid-State Solar-Thermal Energy Conversion EFRC, and MRSEC. The new facility is operating according to the same business model used in the other SEFs. The equipment purchased for the facility (with funding provided by the Eni Solar Frontiers Center) includes an atomic force microscope, an inspection optical microscope, a four-point probe, a variable-temperature He cryostat, a Ti-sapphire laser and tunable laser source, and an infrared (IR) light source and IR monochromater. During its first year of operation (October 2012 to September 2013), 90 users from inside and outside MIT logged a total of 6,907 hours of equipment usage in this new lab.

Collaborations, Outreach, and Knowledge Transfer

Our MRSEC-supported faculty has ongoing collaborations with numerous industrial partners that range from the funding of applied projects (often based on fundamental work carried out within the center) to the development of new technologies and products. We work closely and effectively with MIT programs and centers such as the Materials Processing Center (MPC) and the Industrial Liaison Program (ILP), which connects MIT research to industry. These organizations combined have more than 200 member companies. During this reporting period, MRSEC faculty and/or their group members engaged in at least 70 meetings with representatives from a broad range of different domestic and foreign companies, including visits from industrial representatives, faculty visits to different firms, briefings to company executives, and teleconferences. A partial list of these companies includes 3M, BMW, Boeing, Bosch, Dyson, Honda, Lockheed Martin, Nissan Motor Co., Samsung, Shell, and Unilever.

CMSE contributes to the showcase MIT materials event, the annual Materials Day at MIT program organized by MPC; CMSE co-organizes the poster session and provides input on potential CMSE speakers. One important objective of this event is to connect MIT materials research to managers and researchers from industry and government laboratories. The title of this year's event was "Photonic Materials." Professor Carl Thompson from MPC provided introductory remarks and an overview of the program. The meeting was attended by more than 130 registered guests from industry, government laboratories, hospitals, MIT, and other universities, as well as additional researchers and students from MIT who joined throughout the day on a walk-in basis. Representatives from over 45 US and foreign companies, laboratories, and universities attended the event, including employees of 3M, Energizer, Konica Minolta, LG Electronics, Lockheed Martin, Nissan, Novartis, Osram Sylvania, and Raytheon. The capstone poster event included posters from CMSE students and others from the MIT materials science community. This year, out of a total of 64 posters submitted, 21 were from students and postdocs of faculty supported by CMSE funding. The poster session was judged by a panel of members from MPC's Advisory Board, which includes research managers from industry.

MRSEC-supported faculty presented an overview of their CMSE research in two ILP-sponsored conferences: the 2013 MIT Research and Development Conference (P. Anikeeva, M. Buehler, Y. Fink, S. Gradecak, and K. Van Vliet) and the 2014 MIT Japan Conference in Tokyo (J. Kong and C. Thompson). The Research and Development Conference was attended by more than 250 representatives from companies including 3M, EMC Corp., Jaguar Land Rover, LG Electronics, Lockheed Martin, Novartis, Philips, Procter and Gamble, Raytheon, Samsung, and Siemens. The Japan Conference, which highlighted advances in areas such as energy, materials, electronics, and information technology, was attended by 180 researchers from companies including Canon, Hitachi, NEC Corporation, Ricoh, Toshiba, and Toyota.

Another important mechanism for knowledge transfer is the creation of new companies and businesses (and related jobs). Currently active CMSE-related companies that were started by MRSEC faculty, students, or postdocs include OmniGuide Inc., LumArray, Luminus Devices Inc., QD Vision, Kateeva, WiTricity Corporation, and Svaya Nanotechnologies. These various companies were founded to develop novel devices and components based on discoveries made within the MRSEC program and funded, in several cases, exclusively through NSF. Additionally, Nanosys and Quantum Dot Corporation (bought by Invitrogen) are companies whose technology platform is based in part on CMSE-supported fundamental research. It is estimated that total direct job creation by the most closely CMSE-related companies (OmniGuide, LumArray, Luminus Devices, QD Vision, Kateeva, WiTricity, and Svaya Nanotechnologies) is about 300 jobs and growing.

MIT's Technology Licensing Office is kept aware of new discoveries emanating from CMSE research and helps researchers file patents and issue licenses. During this reporting period, 13 new patents related to MRSEC were issued, and 21 new patent applications/provisional patents are pending.

The center's MRSEC-supported faculty enjoy a high level of outside collaboration. During this funding period, there were a total of 51 collaborations (19 of which were international): 3 industrial collaborations, 40 collaborations with outside academic researchers, and 8 collaborations with government laboratories and agencies (all MRSEC related). In addition, a number of CMSE faculty members supervised students in departmental co-op programs that carry out research projects in a wide variety of industrial laboratories.

During the past year, MRSEC continued one international collaboration and started a new collaboration. Both were forged by MRSEC and have engaged multiple MRSEC-supported faculty members.

In partnership with professor Marisa Beppu at the University of Campinas in São Paulo, Brazil, MRSEC faculty are engaged in a variety of exchange programs including student visits to and from Brazil and extended visiting student research projects at MIT. This past year two MRSEC-supported students, Jonathan Gilbert and Hyomin Lee, visited the University of Campinas through a travel grant from the MIT-Brazil Program; the goal of the visit was to promote knowledge transfer between CMSE research groups and the faculty and students at the university. During their visit, they toured scientific facilities including a nanotechnology facility and the LNLS Synchrotron facility, attended seminars conducted by Brazilian students and postdocs, and presented a number of lectures on their MRSEC research. In the coming months, one graduate student and a postdoc from Brazil will be spending at least six months in MRSEC laboratories engaged in collaborative research.

The objective of the new collaboration with École Polytechnique in France will be to establish a direct line of communication between Polytechnique students and MRSEC faculty. Each fall, MRSEC-supported students will give a presentation to approximately 100 École Polytechnique students, sharing information on such topics as MIT educational and research programs, the repartition between class work and lab work, the research assistantship system and what it entails, and how to choose a research group. A goal will be to recruit École Polytechnique students to come to MIT as interns through MIT's international visiting student program. The special connection made with students through this collaboration will result in better placement of the students in MRSEC and related MIT research groups.

Education and Human Resources

CMSE has 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 the assistant director.

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 and with religious communities and professional organizations.

For the past eight years, CMSE has collaborated with Roxbury Community College (RCC), a minority-rich two-year college in Boston, to make research experiences available to its students. The objective of this dedicated REU program is to engage community college students in current materials research and encourage them to pursue careers in science and engineering. In 2007, the program was expanded to include students from Bunker Hill Community College (BHCC) as well as RCC. Both colleges have significant enrollments of minority students.

Precollege Education

Research Experience for Teachers

For the past 15 years, CMSE has operated a successful RET program. This program brings high school and middle school teachers to MIT to participate in CMSE research. The teachers spend seven weeks immersed in research during the first year of the program and 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, SEF tours, 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. Lesson plans written by the teachers are distributed to other science teachers and used in teacher workshops.

RET Participants, Summer 2013

Name	School/Subject(s) Taught	Research Project or Lesson Plan
Valerie Chambers	Fletcher-Maynard Academy, Cambridge, MA (K–5 science)	Plant xylem water filtration
Talia Clark	Jeremiah E. Burke High School, Boston, MA (physics)	Cation exchange in MOF-74 and MFU-41
Michael Dower	Young Achievers Science and Math Pilot School, Boston, MA (science, technology, and engineering)	Cellular respiration and releasing energy from food lab experiments
Eric Kolifrath	Stoneham Middle School, Stoneham, MA (life science)	Repair of cartilage defects using bone marrow mesenchymal stem cells, growth factors, and self-assembling peptide
Rory Konrad	Somerville High School, Somerville, MA (physics)	Science fair project and report instructions
Jode Lavine	Bunker Hill Community College, Charlestown, MA (engineering)	Characterization of fiber-inspired neural probes

Name	School/Subject(s) Taught	Research Project or Lesson Plan
Sean Müller	Merrimack High School, Merrimack, NH (chemistry)	Driving electroluminescent panels
Katie Semine	Acera School, Melrose, MA (third grade)	Polymerase chain reaction for the 21st-century classroom
Jill Sewell	Swampscott High School, Swampscott, MA (physics, biology)	Light scattering measurements of thin film thickness
Douglas Shattuck	Concord Middle School, Concord, MA (applied technology)	Structural engineering and bridge building
Kimberly Stieglitz	Roxbury Community College, Boston, MA	Constructing the thermogenetic tools for remote cell membrane heating
Amanda Tsoi	Somerville High School, Somerville, MA (biology)	Science fair project and report instructions

Relationships between CMSE and the RET participants extend beyond the summer program. The teachers bring students to campus and arrange for MRSEC researchers to visit their classrooms.

Feedback from recent participants in the RET program indicates that they were satisfied with the program and that it has had a meaningful impact on their teaching. The most frequently cited enhancement of their classroom teaching as a result of their research experience at CMSE is the incorporation of more hands-on lab projects. The program participants often share their units and RET experience with fellow teachers at their schools and at regional and national meetings.

Science Teacher Enrichment Program and Women's Technology Program

CMSE offered its Science Teacher Enrichment Program (STEP) for the 12th time in the summer of 2013.

STEP consists of a one-week workshop, "Dustbusting by Design," that focuses on increasing middle and high school teachers' content knowledge and providing them with experience in engineering design. The workshop correlates with the Massachusetts state science learning standards. Participants spent the first four days of the program in a machine shop on campus learning about the design challenges associated with the motor in a hand-held vacuum and then immersed themselves in the engineering design process as they constructed motors of their own design. The remainder of the week was devoted to presentations by CMSE researchers and a seminar on teaching the design process in K–12 classrooms. The 2013 program featured RET participant Sean Müller, who shared classroom polymer demonstrations he has developed, and a presentation by professor Mircea Dincă on his energy storage research. The lab portion of the program was simultaneously taught to 40 high school girls in the Women's Technology Program.

Participants in STEP received a small stipend and professional development points. They were recruited from local school districts, from former applicants to the RET program, and through other MIT-based programs for educators. Five teachers participated in the 2013 STEP (a middle school science teacher and four high school physics teachers). Entrance and exit surveys were used to determine how well the workshop met the teachers' professional needs. All of the 2013 respondents indicated that they found the program valuable and that it met or exceeded their expectations. One teacher reported that the workshop made him rethink the design of part of his classroom curriculum. Another implemented a modified version of the motor-building class with two physics classes at his high school. A third participant commented, "I really don't think anything else would have as big an effect on my students as this kind of program."

A companion effort to STEP is CMSE's collaboration in the Women's Technology Program (WTP) in EECS. In this four-week summer residential program, 40 high school girls from across the country 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. CMSE invites the WTP participants to join the lab portion of STEP to gain hands-on engineering experience. For the past 11 years, this has been an extremely successful collaboration. WTP alumni report that this motor-building lab is an exciting part of the program. CMSE continued to support WTP by providing the curriculum and supplies for this part of the program in 2013 and will continue to do so in 2014.

Workshops and Public Events

MRSEC faculty and students contributed content to a variety of programs and events on campus, at local schools, and at other public venues.

CMSE's education leader, professor Steven Leeb, leads several outreach efforts each year. Each spring he participates in the annual Belmont Science Night held at the Winbrook School. He presented to 175 attendees at this year's Science Night on April 3. In addition, for the fifth year, he taught a four-session materials and energy class to 25 high school students on campus to participate in the Research Science Institute (RSI) in summer 2013. RSI is a well-established national six-week research program for outstanding high school students sponsored each year by the Center for Educational Excellence. MIT also hosts about 50 science teachers for a week each June for the Science and Engineering Program for Teachers. This professional development program has been in place for 24 years and features faculty lectures on new frontiers in science and engineering research as well as hands-on workshops. Professor Leeb presented a talk on energy research during the 2013 program.

Additional MRSEC faculty and students contribute to local outreach events. Professor Gareth McKinley participated in the Acton Discovery Museum's 2013 National NanoDays celebration as a guest scientist. During the three-hour event, he demonstrated nanotubes, buckyballs, liquid crystals, shape memory metals, superhydrophobic coatings, and a ferrofluid to 30–40 children and their families. Professor Angela Belcher presented the keynote lecture at the Boston Area Girls STEM Collaborative's sixth annual "S.E.T. (Science, Engineering, Technology) in the City" on April 12. This full day of STEM (science, technology, engineering, and mathematics) career exploration for high school girls took place on several local college campuses, with approximately 160 girls registering for the event. Finally, MRSEC regularly participates in the annual Cambridge Science Festival, a 10-day, citywide public celebration showcasing Cambridge as a leader in science, technology, engineering, and math. It features a wide range of activities including a science carnival, typically attended by more than 200 people of all ages, that incorporates dozens of exhibits and demonstrations. MRSEC graduate students demonstrated polymers and a non-Newtonian fluid at the 2014 carnival.

Science and Engineering Program for Middle School Students

The center has operated a science and engineering program for seventh- and eighth-grade students from two Cambridge public schools for the past 22 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 summer week of hands-on and inquiry-based science and engineering classes for students from each school. During the summer of 2013, 24 seventh- and eighth-grade students attended with their science teachers. Seven of them were girls, and 13 were members of underrepresented minority groups.

The students participated in hands-on activities presented by faculty, staff, graduate students, and undergraduates. The 2013 program included classes on glassblowing, metal casting, ultraviolet light, simple DC motors, electric circuitry, polymers, and solar cells, as well as a tour of the MIT Museum. In group discussions at the end of each week, the students were able to describe the material presented and identify at least one new concept that they learned during the week (i.e., that nylon is made of two chemicals). On exit surveys, students described the week's activities as "fun," and all of the respondents said that they would recommend the program to friends.

Undergraduate Education

Undergraduate Research Opportunities Program

CMSE provides opportunities for MIT undergraduates to participate in MRSEC research through MIT's Undergraduate Research Opportunities Program (UROP). Participants in this program work on MRSEC research on a part-time basis during the academic year and full time during the summer. MRSEC typically supports three students each academic term and three during the summer. UROP students sometimes continue their research beyond one term. Also, MIT provides funding for a limited number of UROP participants, and some of them work on MRSEC research. During this reporting period, MRSEC directly supported five undergraduates. Two of them were women and one was an underrepresented minority student. CMSE faculty report that an additional eight students (six of whom were women) working on their MRSEC research were supported by MIT directly or worked for academic credit.

CMSE-Funded UROP Students, June 2013–May 2014

Student	Department	Project
Nelson Brock	Mechanical Engineering	Design of prototyping kits for educational purposes
Tina Chen	Materials Science and Engineering	Investigation of the conductivity of perovskite catalysts for oxygen evolution and reduction reactions
Lucas Orono	Physics	Hybrid topological insulator graphene devices
Caitlin Sample	Materials Science and Engineering	Poly(vinyl alcohol)-based hydrogen-bonded multilayer films
Kawin Surakitbovorn	Physics	AC/DC mode switch for a doubly fed induction machine

Summer Research Internship Program

In collaboration with MPC, CMSE sponsors the Summer Research Internship Program (through the NSF REU program). The program's major goals are to provide undergraduates from other institutions 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 received 180 applications for the summer of 2013, which were reviewed by a committee consisting of the CMSE director and staff from both centers. Participants were chosen from this pool on the basis of academic performance, interest statements, and faculty references. The 18 students accepted into the program for the summer of 2013 included nine women and six students from underrepresented minority groups.

The students were paid stipends and worked full time for nine weeks. Most of them lived in a dormitory on campus. Weekly meetings were 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 completed the program by producing posters that reported on their summer's research. The resulting poster session was held during the final week and was open to the entire MIT community. It included posters produced by participants in CMSE's RET and community college programs as well and served the dual purpose of functioning as a final report by the interns and teachers and informing the broader MIT materials community about the wide range of research supported under the auspices of the two centers. The CMSE/MPC program is well established as a quality internship program on campus. Consequently, other organizational units seek to fold their summer undergraduate researchers into the program. Last summer, the stipends of two students in the REU program (Joseph Andrade and Alvin Mercedes) were paid by the DOE-funded Solid-State Solar-Thermal Energy Conversion Center. These two students were selected from the pool of applicants to the REU program and participated fully in the program.

CMSE/MPC Summer Interns, 2013

Name	Home Institution/Major	Research Project
Joseph Andrade	Vassar College/physics, mathematics, economics	Investigating magnetic tunnel junctions with the 3D topological insulator Bi2Te3
Megan Beck	Boise State University/materials science and engineering, mathematics, applied mathematics	Optimization of lead sulfide (PbS) quantum dot synthesis for monodispersity
Raul Calzada	Texas A&M University/chemical engineering	Synthesis of new ligands for MOF-74
Scott Danielson	University of Pennsylvania/ chemical and biomolecular engineering	Microfluidic devices based on carbon nanotubes and polymer multilayers for PSA detection
Joanna Denton	University of West Georgia/ chemistry	Ferrimagnetic triangular nanopillars
Felix Elias	Universidad del Turabo/computer engineering	Dynamic parallelism using graphics processing units to solve hybrid fluid dynamics
Wendy Feinstein	University of Massachusetts, Amherst/chemical engineering	Sol-gel-derived synthesis of tungsten carbide nanoparticles
Sarah Goodman	Rutgers University/chemistry	Chemical etching study of germanium and silicon
James Haynes	North Carolina A&T State University/civil engineering	Submarine shaft life enhancement using a composite weld overlay
Mila'na Jones	Xavier University/chemistry, mathematics	Synthesis of magnetic nanoparticles for heat stimulation
Kari Kusler	University of North Dakota/ chemistry	Investigation of synthetic silk block copolymers using molecular dynamics simulations
David Mackanic	Virginia Tech/mechanical engineering	M13 virus template 3D nanostructures as a versatile template for energy applications
Jacob McAlpin	Louisiana State University/ materials chemistry	Density functional theory study of stacking faults in hexagonal close packed metals
Alvin Mercedes	Universidad del Turabo/computer engineering	Optical-vortex-trapping nanostructure design for efficient absorption and nanoscale manipulation of light
Rachel Philiph	Iowa State University/materials engineering	Macrophase separation using block copolymer blends
Robert Ramirez	Columbia University/chemical engineering, applied mathematics	Thin conductive hydrogel membrane produced by electrophoretic deposition
Stephanie Tzouanas	Rice University/bioengineering	Material characterization and selection of an implantable intraperitoneal drug release device for the treatment of advanced ovarian cancer
Emma Vander Ende	Northern Kentucky University/ chemistry	Polymer-wrapped carbon nanotubes as in vitro dopamine detectors

The nine-week summer internship program begins with a three-day symposium during which faculty present their research and describe the projects available for the interns. At the end of the three days, the interns select their projects for the summer. Throughout the summer, the interns and the REU students participate in weekly mentoring meetings and seminars. They also present posters at the RET/REU poster event.

CMSE participates in the MRSEC cross-site REU assessment. Interns' responses on the 2013 survey indicate that, overall, they felt the REU program was a positive experience that contributed to their professional development and career plans. All of the interns expressed satisfaction with the guidance they received from their mentors, and 96% were satisfied with their research project. In addition, all of the students indicated that they felt the experience greatly increased their confidence in their ability to contribute to science, 95% reported that the program prepared them for graduate study, and 57% reported being more likely to enroll in a PhD program after the summer (relative to their intentions before the program). Finally, 90% indicated that the program helped clarify which field of study they would pursue in graduate school.

Diversity Enhancement Activities

CMSE has a history of promoting and encouraging traditionally underrepresented minority groups and women to participate in materials research. This is accomplished through educational outreach efforts, special programs for graduate research assistants, and efforts to coordinate activities with faculty, postdoctoral associates, and graduate and undergraduate students. A few of these activities are summarized below.

Community College Program

CMSE's Community College Program (CCP) is another targeted REU program designed to enhance the diversity of undergraduate participants in MRSEC's research and education programs and to broaden participation among science and engineering professionals. Four students from two local community colleges that enroll significant numbers of minority students (50% at one and 64% at the other) participate in CCP each summer. Over the nine years that the program has been in place, 67% of the participants have been minority students and 52% have been women. One student with a disability participated.

Typically, community college students do not have opportunities to gain research experience at their home institutions. By participating in CCP, they learn research and technical lab skills that increase their confidence and prepare them to pursue bachelor's degrees and science and engineering careers. To promote their professional development, they also participate in the weekly REU meetings to learn about intellectual property, the graduate school admissions process, and leading-edge developments in materials research. The MRSEC director and education officer meet separately with the CCP students as a group at least twice each summer to discuss their research and their career plans. In these meetings students have reported that, in addition to building their confidence in their ability to perform science and engineering activities, their experience at MIT broadens their knowledge of possible science and engineering careers and provides a more realistic picture of graduate work. Since the program's beginning, 70% of the former participants who have finished their community college careers have enrolled in four-year colleges. Of those, one recently completed a master's degree in biotechnology, one has gone on to medical school, and two are enrolled in science PhD programs. A fifth student completed her BS in chemical engineering and is now pursuing her MBA while working at Abbott Laboratories. Five CCP participants found employment after completing an associate's degree. An additional student who came to the program with a BS is now working as an environmental engineer. Seven students are still enrolled at community colleges, and the status of five other participants is unknown.

In 2013, all four of the participating students were men, and one was a minority student. In addition to the four students funded by CMSE, an additional RCC student who had other support participated in CCP, working in professor Brian Wardle's lab. Students spent nine weeks on campus engaged in research as members of faculty-led groups for which they received a stipend. They chose their research projects from several presented by the MRSEC director during a preliminary seminar. CCP participants presented their research in the RET/REU poster session in August.

CCP REU Participants, 2013

Name	Home Institution/Major	Research Project
Ferdinand Dowouo	Bunker Hill Community College/ electrical engineering	Injectable hydrogels from artificially engineered proteins for tissue reinforcement
Eric Friedman	Roxbury Community College/ engineering	Energy harvesting through thermopower waves
Ruslan Khachatrian	Bunker Hill Community College/ chemical engineering	Steel plate layering
Tianyuan Liu	Roxbury Community College/ engineering	Counting primary loops in artificial protein gels
Mark Payne (supported with non-CMSE funds)	Roxbury Community College/ engineering	Hierarchical carbon fiber composites: assessing in-plane mechanical properties at the unidirection composite scale

MRSEC collaborates with professor Polina Anikeeva to broaden the impact of its partnership with RCC and BHCC. With CMSE support and her NSF CAREER grant funds, she embarked on a multiyear plan to engage BHCC and RCC faculty and students in her lab's research, thus extending MRSEC's outreach to a wider group of community college students and faculty. One professor from each institution spent the summer of 2013 doing research with Professor Anikeeva's group as a participant in CMSE's RET program. The intention is for the RCC and BHCC faculty to integrate their research experience into their classroom teaching. CMSE provided the professors' stipends and the cost of supplies to implement a related classroom unit at RCC. In addition, Professor Anikeeva visited both community colleges in October. She delivered a lecture titled "Neuroprosthetics: Electronic, Optical and Magnetic Approaches" at the RCC Honors/Phi Theta Kappa Seminar and at the BHCC STEM Speaker Series. Approximately 30 students and several faculty attended each event. This coming summer, another two professors will work in Professor Anikeeva's lab. They will be joined by a student from each school.

Partnership with Universidad Metropolitana

In 2008, MRSEC formed a collaboration with Dr. Juan Arratia at the Universidad Metropolitana (UMET) to enhance the research experiences of students at the three Puerto Rican universities affiliated with the Ana G. Mendez University System (UMET, Universidad del Turabo, and Universidad del Este). Dr. Arratia refers students to the MPC Summer Research Internship Program (REU). At least two intern positions a year are set aside for these students. A goal of the partnership is to recruit and retain Puerto Rican science, technology, and engineering graduates. Since its inception, 12 students have participated in the program, and an additional two students spent two weeks at CMSE working with graduate students to learn to use research instruments in the SEFs. Three of the students are still completing their undergraduate studies, and another six are currently pursuing graduate degrees. Of the remaining students, two are working as engineers, and the career status of the other three is unknown. In addition to their research at MIT, undergraduates who participate in the REU program contribute to UMET's outreach to high school students in the San Juan area.

Enhancing Diversity within Existing Programs

To increase minority participation in the REU program, CMSE directly advertises the program to minority-serving institutions. In the fall of 2013, approximately 450 letters with attached recruitment flyers were emailed to principal investigators at NSF-funded Centers of Research Excellence in Science and Technology, Historically Black College and University Undergraduate Programs, Model Institutes of Excellence, Louis Stokes Alliances for Minority Participation, and Tribal Colleges and Universities Programs. CMSE has also advertised its REU program via the Institute for Broadening Participation's online directory of REU programs. In addition, the education director encourages former minority participants to refer friends and other students at their home institutions to the internship program. The number of applications from women and minority students has been gradually increasing since the beginning of the grant. Applications recently received for the 2014 program showed another increase in the percentages of women (35%) and minority (16%) applicants relative to the preceding year. To further increase diversity in the REU program, the center, as mentioned, runs collaborative programs with two local community colleges and the Universidad Metropolitana, all of which serve underrepresented minority students.

Recognizing the importance of increasing diversity in the pipeline of future scientists and engineers, CMSE seeks to impact the classroom experience of minority students by strengthening the materials content knowledge of their science teachers. CMSE is committed to achieving at least 50% participation by teachers from schools attended by significant numbers of underrepresented students (above 50%). Five of the 10 teachers in the 2013 RET program were from such school districts in Massachusetts (two from Boston, one from Cambridge, and two from Somerville), and both community college professors who participated in RET teach at institutions in which underrepresented minority student enrollments are 50% or higher. In addition, CMSE directly engages local middle school students through the Science and Engineering Program for Middle School Students. Students who participate in this program are drawn from two Cambridge public schools where approximately 50% of the registered students are from underrepresented minority groups. Although the number of female and minority attendees varies from year to year, the program reliably reaches a diverse group of young people. Participation over the course of the current grant averages about 40% female and 60% minority students. In the summer of 2013, 29% of the participants were girls and 54% were minority students.

Partnership with North Carolina A&T State University

Recently, MRSEC partnered with professor Elham Fini at North Carolina A&T State University (NCA&T) to provide at least one REU slot to a student from this historically black university during the summers of 2012 and 2013. Dr. Fini, an assistant professor of civil engineering at NCA&T, spent the summer of 2011 doing research at MRSEC as a participant in an NSF-funded leadership development institute, and she returned in 2012 to continue her collaboration with professor Markus Buehler. In 2011, CMSE provided funds to help Professor Fini bring a group of her students to MIT to learn about graduate study at a leading research university. During the course of their visit, the students met with the MRSEC director, other faculty, and dean for graduate education Christine Ortiz. A description of the REU program was included in the presentation, resulting in applications from NCA&T students for the first time. Civil engineering major James Haynes participated in the 2013 program.

Materials Research Facilities Network Partnerships

Through an NSF Materials Research Facilities Network (MRFN) supplement, MRSEC has strengthened its partnerships with minority-serving institutions by providing access to its SEFs for their faculty and students. Exciting plans are in place for the faculty and their students to be trained to use the instruments to further their research projects beyond what is possible on their home campuses and to build on that experience to enhance undergraduate teaching. Professor Ellie Fini will continue, through an MRFN-sponsored project, to use the X-ray diffraction and atomic force microscopy instruments. She expects to incorporate this experience into a graduate course she is developing on sustainable material characterization. Professor Oliva Primera from UMET will make use of the MRFN funds to expose her students to characterization techniques. She will bring two undergraduates with her to CMSE in July 2014 to use the TEM and scanning Auger nanoprobe to characterize gold and silver nanoparticles and CdSe quantum dots fabricated at UMET's Nanomaterials Science Laboratory (NSL). Back in Puerto Rico, the students will share their acquired knowledge with other students in NSL materials characterization workshops. Professor Maria del C. Cotto-Maldonado from the Universidad del Turabo and professor Nicole Zacharia from the University of Akron will also bring students to CMSE in the summer of 2014 to complete their research projects.

Postdoctoral Mentoring

CMSE has developed a robust postdoctoral professional development program. Over the past year, 16 postdoctoral associates worked on MRSEC research, 15 of whom were paid directly by the center. CMSE launched its postdoc mentoring program in 2010 with a director-led meeting of CMSE postdocs to identify their professional development needs and topics they would like to see addressed. As a result, a postdoc advisory committee was formed to provide input to the director about activities and services that would be beneficial with respect to professional development. In 2011, with input from this committee, CMSE inaugurated a seminar series that features annual professional development events jointly sponsored by CMSE and a partnering MIT academic department. All postdocs working with CMSE faculty are invited to participate in the seminars, whether or not they are supported by MRSEC. The initial seminar, held in January 2011 and cohosted by DMSE, featured a panel discussion focusing on career paths and balancing professional and family lives. CMSE partnered with the Department of Chemical Engineering to present the second seminar in 2012. At this event, a panel of faculty presented advice on finding and securing faculty positions, including information on the search process, interviewing, and negotiating a startup package. A total of 75 postdocs attended these two events. On exit surveys, attendees offered positive feedback on the two seminars. Similar seminars in partnership with other academic departments will be scheduled in the future to address topics identified by the advisory committee.

This year MRSEC began a series of master classes designed to enhance postdocs' oral and visual presentation skills. The classes are co-sponsored with related academic departments and are taught by Felice Frankel, CMSE research associate and science image specialist. Frankel has worked with scientists and engineers for many years and has published two books. Her book *Visual Strategies: A Practical Guide in Graphics for Scientists and Engineers* forms the foundation of the master classes, which consist of a large-group lecture followed by small-group workshops. During the workshops, participants critique and refine images from their own research. A total of three master classes (co-sponsored by the Departments of Mechanical Engineering, Materials Science and Engineering, and Chemical Engineering) were held during the fall of 2013. Responses from the participants were so positive that Frankel taught an additional workshop during IAP in January. Altogether, approximately 300 postdocs and graduate students attended the four master classes.

In addition to the seminar series, the MRSEC director has been meeting individually with postdocs to offer career development and job search advice. The Office of the Vice President for Research (VPR) oversees a robust program of mentoring and professional development activities for postdoctoral researchers that includes a seminar series, workshops, and a library of online resources. The office also supports the postdoc-led MIT Postdoctoral Association, which sponsors speakers, workshops, career fairs, writers' groups, and social events. The postdocs are informed of this broad range of opportunities through a listserv maintained by VPR.

Finally, as part of its postdoc mentoring plan, CMSE encourages postdocs to hone their science communication and presentation skills by teaching in the center's education programs. In addition to mentoring REU students, they regularly participate in CMSE's middle school, high school, and teacher programs.

Administration, Management, and Research

Our MRSEC program is administered by a proactive and effective management team that responds quickly to emerging needs of the program. Currently, seven administrative and seven SEF staff support the program. Administrative staff include an education officer, facilities and safety coordinator, financial administrator, financial and operations assistant, assistant to the director, assistant director, and director. SEF staff include one technical associate, four research specialists, a project technician, and a research scientist. The CMSE director reports directly to the vice president for research and associate provost, the assistant director reports to the director, and all other staff, including the facilities manager, report to the assistant director. Our current director also serves as CMSE's chemical hygiene officer. CMSE currently has a faculty education program leader who marshals our educational outreach plans with our education officer.

We are excited to announce that professor Angela Belcher has agreed to take on a new role in our center as a faculty special projects coordinator. In this role, she will be working with RET participants to develop hands-on teaching modules and related video content. The overall objective is to create a new pipeline of future engineers and scientists for fields vital to the future of the United States through the use of cutting-edge, hands-on learning exercises. For example, a collaboration with a local RET teacher has led to the development of an inexpensive ($50–$100) polymerase chain reaction machine that allows K–12 students to learn about DNA biotechnology.

CMSE, recognizing the financial burden MIT junior faculty face in utilizing large experimental facilities for research needs, launched the CMSE Junior Faculty SEF Award program in 2011 to assist these faculty members in accessing the CMSE shared experimental facilities. The faculty who were awarded funds during 2013 found the program very helpful, and it has been decided to continue the program into the future and extend each award for a two-year period, allowing more time for the junior faculty members to use this funding. Contingent on the availability of center discretionary funds (this program is supported by funds distributed to CMSE from technology licensing revenue), CMSE will fund five to seven individual awards per year to MIT assistant professors at a level as high as $5,000 for each award. Each award will last for two years and can be applied only to user fees in CMSE shared experimental facilities. These awards are restricted to faculty engaged in research activities related to aspects of materials science and engineering as practiced at CMSE. One- to two-page research proposals for these awards will continue to be solicited from junior faculty throughout the MIT materials community each year and reviewed by the center director, who will make awards based on the strength of the faculty proposal and the financial need justification. The following MIT junior faculty (assistant professors) received these awards for FY2014: Joseph Checkelsky (Department of Physics), Antoine Allanore (DMSE), and Elsa Olivetti (DMSE).

CMSE has continued to support the joint CMSE/DMSE colloquium series started in 2005 with the Department of Materials Science and Engineering and expanded in 2007 to include the Materials Processing Center. The DMSE/CMSE/MPC partnership allows the center to pool resources and bring in speakers from outside of MIT. The objectives of the colloquium series are to provide an opportunity for faculty, research staff, and students from the CMSE community to meet on a regular basis to hear about the latest breakthroughs in materials research and to inform the greater MIT community about materials research. A total of six lectures were held in this period featuring speakers from around the country and world. The fall 2013 speakers were Ludwik Leibler (ESPCI ParisTech), Bethanie Stadler (University of Minnesota), Ian Robertson (University of Wisconsin, Madison), and Peter Day (Sheffield University). William Curtin (École Polytechnique Federale de Lausanne) and Zhenan Bao (Stanford University) presented talks in spring 2014.

CMSE also continues to serve as a sponsor of the Boston Area CarbOn Nanoscience (BACON) meetings by providing funding for the food at these events. Professor Pablo Jarillo-Herrero is the organizer of the MIT portion of the programs. The BACON monthly meetings, now in their sixth year, bring together researchers in the Boston area to discuss their recent work and exchange ideas about carbon nanotube and graphene research in an informal setting. Each meeting consists of two talks (typically by students or postdocs) that are open to everyone and feature speakers from MIT, Harvard, and Boston University.

CMSE participated in and co-sponsored a "Future Faculty Workshop" in June 2014. In the broader context of promoting diversity at the faculty level, these very successful two-day workshops, originated by professors Tim Swager (MIT) and Rick McCullough (Carnegie Mellon University), seek to provide intensive mentorship to minority students and postdoctoral fellows interested in pursuing careers in academics in the areas of materials science, chemistry, and chemical engineering.

During this reporting period, CMSE also pledged sponsorship for the American Chemical Society's 88th Colloid & Surface Science Symposium, held in June at the University of Pennsylvania in Philadelphia. This symposium was co-organized by the University of Pennsylvania MRSEC and represents one of the premier annual soft matter conferences in the United States, with about 600 technical attendees including representatives from industry.

In addition, CMSE co-sponsored a Partnership for Research and Education in Materials (PREM) poster session at the Materials Research Society fall meeting in December 2013. PREM students from across the United States came to Boston for the meeting and to participate in the poster instruction session and competition. CMSE arranged for transportation from the meeting to MIT and Harvard so that students could tour the MIT SEF labs and the MRSECs at both institutions. Director Michael Rubner gave an overview presentation to the students that highlighted research ongoing at CMSE and led a discussion of career possibilities in materials science.

CMSE also hosts the MIT-wide Facilities Managers Group. This group was formed to better coordinate the synergistic activities of the large materials community at MIT. The CMSE director and one of the CMSE SEF managers, chosen each year by the CMSE director, chair the group, and meeting arrangements are made by CMSE headquarters staff.

CMSE activities are guided and supported by three internal committees and one external committee. The Committee on CMSE, Internal Advisory Committee, and Space Committee are internal MIT committees that offer guidance to CMSE on research, large equipment purchases, space, safety, and educational matters. The Science and Engineering External Advisory Board (SEEAB) offers guidance on ways to enhance collaborations and supports major efforts in long-range materials research and engineering. During this reporting period the CMSE director reconstituted SEEAB, adding members and broadening the perspective of the board. The following individuals now serve on the board: Dr. Leonard Buckley, director of the Science and Technology Division at the Institute for Defense Analyses; Dr. Edwin Chandross, a materials chemical consultant; Dr. Mark Ketchen, manager of design/technology integration at IBM; Dr. James Misewich, associate laboratory director for basic energy sciences at the Brookhaven National Laboratory; Dr. Eva Andrei, a professor in the Physics and Astronomy Department at Rutgers University; Dr. Rama Bansil, a professor in the Department of Physics at Boston University; Dr. Sharon Glotzer, Stuart W. Churchill collegiate professor of chemical engineering at the University of Michigan; and Dr. Raymond Samuel, assistant dean of the School of Engineering and Technology at Hampton University and an associate professor in the Department of Chemical Engineering. These new members offer a wide range of expertise and experiences that will further enhance the board's effectiveness in guiding CMSE in all of its research, outreach, and diversity activities.

Michael F. Rubner
Director
TDK Professor of Materials Science and Engineering