MRSEC PROGRAM
ANNUAL REPORT AND CONTINUATION REQUEST

For the Period November 1, 2014 – July 31, 2015
Under Grant No. DMR-1419807

Submitted to
THE NATIONAL SCIENCE FOUNDATION
by
The Center for Materials Science and Engineering
Massachusetts Institute of Technology Cambridge, Massachusetts

July 31, 2015
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1. EXECUTIVE SUMMARY

1a. Center Vision and Director’s Overview: The underlying mission of the CMSE MRSEC 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 center works to bring together the large and diverse materials community at MIT in a manner that produces high impact science and engineering typically not realized through usual modes of operation. The MIT MRSEC enables collaborative interdisciplinary research between MIT faculty and the researchers of other universities, industry and government laboratories. Synergistic activities with key organizations at MIT including the Materials Processing Center (MPC), Industrial Liaison program (ILP) and strategically aligned departments in the Schools of Science and Engineering are leveraged to maximize the impact enabled by MRSEC funding including the center’s wide-ranging outreach activities. The MRSEC maintains professionally staffed, state-of-the-art shared experimental facilities (SEF) that provide key infrastructure support to researchers in the local area and the nation.

Research Programs: CMSE’s current research portfolio includes three IRGs and four seed projects: the IRGs and seeds are highlighted below. The total number of faculty supported in this research program during this grant cycle was 27.

IRG-I) Harnessing In-fiber Fluid Instabilities for Scalable and Universal Multidimensional Nanosphere Design, Manufacturing, and Applications (Fink and Soljačić co-leaders): This IRG explores fundamental issues associated with multi-material in-fiber fluid instabilities and uses the resultant knowledge to develop a new materials-agnostic fabrication approach for the creation of nanospheres of arbitrary size, geometry and composition. This research sets the stage for discoveries, both fundamental and applied, in areas ranging from novel neuronal interface devices to delivery vehicles for pharmaceuticals, and potentially in the chemical and electronics industries.

IRG-II) Simple Engineered Biological Motifs for Complex Hydrogel Function (Ribbeck and Doyle co-leaders): This group seeks to understand the fundamental biology, chemistry and materials science underlying the unique properties of biological hydrogels and use this knowledge to design and create synthetic mimics that have the potential to revolutionize the design of water purification technologies and a range of biomedical applications.

IRG-III) Nanoionics at the Interface: Charge, Phonon, and Spin Transport (Ross and Yildiz co-leaders): This IRG seeks to discover the coupling mechanisms between oxygen defects and the transport of phonons, spin and charge at the interfaces of complex oxides. The resultant new knowledge will guide the design of materials for the next generation of miniaturized and high-efficiency devices for energy conversion and for information processing and storage.

Seed 1) Chemically Modified Carbon Cathodes for High Capacity Li-O₂ Batteries (Yogesh Surendranath, Dept. of Chemistry): This seed seeks to improve the long-term performance of Li-O₂ batteries by developing electrode surface treatments that inhibit the growth of insoluble Li₂O₂ precipitates. Seed 2) Interface Engineering of Silicon-Oxide Core-Shell Nanorods for High-Efficiency Water Splitting Photocatalysts (Alexie M. Kolpak, Dept. of Mech. Eng.): This seed utilizes computational methodologies to explore and optimize the photocatalytic water splitting properties of Si-TiO₂ core-shell nanorods in solar energy conversion schemes. Seed 3) Single Crystal Study of Electronic Topology and Correlation (Joe Checkelsky, Physics): This seed seeks to grow single crystals of topological materials with significant electronic correlation to explore new states of matter with novel magnetic and transport properties. Seed 4) Direct Deposition of Catalysts on Porous Metallic Foams for Efficient CO₂ Electroreduction (Fikile R. 1
**Diversity Activities:** During this past funding period, our efforts to enhance diversity in our various educational outreach programs (90 participants, including middle and high school students, teachers, undergraduates and community college students), yielded 72% women and 8% minorities. Recruiting efforts to increase the number of applicants from women and minority students have yielded steadily increasing numbers. Key programs that target women and minorities such as the Women’s Technology Program (WTP), the Universidad Metropolitana (UMET) Program in Puerto Rico, the Middle School Program and the Community College Program continue to be highly successful and praised by the participants. In the WTP case, 546 young women have participated in this program since its inception. Of the 390 who have reported college majors at this point, 331 chose to major in science, engineering or math. Strong support from MRSEC supported faculty, graduate students and post-doctoral associates continues to fuel these various activities and ensures that the programs remain innovative and attractive to participants. Since the beginning of the community college program, 32 (59%) of the participants have enrolled in four-year colleges. Of those, one went on to medical school and three others are currently pursuing graduate degrees in science and engineering. Another is earning an MBA. In our research programs during this funding cycle, 28% of participants were women and 7% minorities (includes, faculty, graduate students and post-doctoral associates supported by the program).

**Education Outreach Activities:** CMSE educational outreach programs encompass a broad range of activities and age levels with participation from middle school students and teachers, undergraduates (REU), and high-school students and teachers (RET). During this funding period, CMSE had 90 direct participants in the various programs, and approximately 470 students, teachers, parents and members of the public took advantage of the numerous community outreach activities to which MRSEC faculty and students contributed. Long-term relationships established with teacher participants of our various programs have resulted in ongoing student/teacher field trips to MIT as well as MRSEC faculty presentations at local schools. This past year, CMSE faculty contributed to a high school student Research Science Institute (RSI) (40 student attendees), and the Science and Engineering Program for Teachers (30 science teachers). In June of 2015, Ms. Felice Frankel, Research Specialist at CMSE, launched a new MIT edX on-line course entitled “Making Science and Engineering Pictures: A Practical Guide to Presenting Your Work”. This course teaches scientists how to best present the important results of their research with the use of images and graphics. Over 8,500 participants registered for the course.

**Shared Experimental Facilities (SEFs):** The SEFs (totaling 11,600 sq. ft. of space) represent a critically important component of the MRSEC and, indeed, the broader MIT research landscape. CMSE currently runs four major facilities: Materials Analysis and Preparation; Electron Microscopy; Nanostructured Materials Growth; and Metrology and X-Ray Diffraction. This past year, more than 1,050 individual users, from both inside and outside of MIT, utilized these facilities to conduct research, engage in educational outreach activities and teach MIT laboratory classes.

**Materials Research Facilities Network Supplement (MRFN):** During this funding period, four faculty and their students utilized MRFN funds to spend up to a week within our SEFs analyzing research samples and getting trained on various instruments. The faculty were from Bunker Hill Community College (Mass), North Carolina Agricultural and Technical State University, Universidad Metropolitana in Puerto Rico, and U. Estadul de Campinas in Brazil. One of the
students from Puerto Rico who came to MIT was an oral presentation symposium winner with a talk based on results generated with MRFN funds.

**Industrial Outreach and Knowledge Transfer Activities:** MRSEC-supported faculty presented an overview of their CMSE research in three MIT-sponsored conferences: the MIT Research and Development Conference; the MIT Brazil Challenge of Innovation Conference; and the MIT China Conference in Wuxi. More than 1,050 representatives attended these conferences from various companies and universities. In addition, MRSEC faculty and/or their group members engaged in about 57 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. As part of a center-driven international collaboration, a number of new activities were launched with Professor Marisa Beppu at the U. Estadual de Campinas, São Paulo, Brazil, including 6-month research visits by a Brazilian graduate student and post-doc.

**Center Management activities:** The CMSE director has been actively involved in the design and planning of the new MIT-Nano building to be completed in 2018. This past 6 months, the emphasis has been on establishing a governance model for the new building. The new building will house primarily shared experimental facilities including the CMSE Electron Microscopy, X-ray, and Surface Analytical shared experimental facilities.

**1b. Center Research Accomplishments for Current Reporting Period**

**Intellectual Merit:** IRG-I research is directed at the development of unique, multi-component nano-structured fibers and nano-particles through the use of a newly discovered processing paradigm involving nonlinear fiber fluid instabilities. Using this approach, this group has developed a number of methodologies that make it possible to selectively break up a semi-conducting core into discrete spheres while maintaining continuous regions of conductive electrodes connected to the spheres. The net result is active, in-fiber electronic devices with >100,000 devices per meter of a fiber, all obtained through a one-step assembly process. This group has also implemented a laser-induced capillary breakup setup and used it to create silicon spheres. The laser setup consists of two lasers with different wavelengths, one of which is mainly absorbed by the fiber cladding and other that is mainly absorbed by the fiber core. Thus, a high controllable temperature profile is obtained. IRG-I researchers have further demonstrated that it is possible to fabricate a meter-long crystalline silicon-core, silica-cladded fiber from a preform that does not contain any elemental silicon but rather aluminum and silica (glass). On the theoretical side, a large-scale parallel Stokes solver has been developed that better scales up to the experimental parameters of the fiber drawing process.

In the applications area, IRG-I researchers are developing synthetic fiber scaffolds that may eventually replace nerve autografts for peripheral nervous system repair in the clinic. In order to better integrate these scaffolds with severed nerves, this group is moving past the current passive structures with cylindrical geometries and creating grooved geometries that improve axonal growth by up to 2 times; a result of the alignment of the developing processes and cell bodies along the grooved topographic features. Next steps will involve combining the topographic features with optical stimulation capabilities and integrated electrodes for monitoring of neural activity during axonal growth and development.

Metallic nanoparticles are well known for strong but narrow visible-range extinction peaks due to plasmon resonance effects. This group hypothesized that by normalizing optical extinction to particle volume ($\sigma_{ext}/V$) over a broad range of incoming wavelengths, extinction coverage
produced by the smallest possible particle could be maximized over the entire visible range. They have now experimentally verified prior theoretical research by demonstrating that oblate ellipsoid nanoparticles are able to extinguish visible light normalized to nanoparticle size more efficiently than almost any other shape. High efficiencies were achieved, up to 100% over the entire visible range. Another important optical parameter is the optical scattering efficiency \( Q_{\text{sca}} \) (defined as the ratio of the scattering to geometric cross sections) of particles. Typically this is altered to achieve maximum opacity in thin layers without absorption, by increasing the refractive index, an approach fundamentally limited by naturally available materials. IRG-I research, however, has shown that multilayer dielectric particles with controlled radial structure and high refractive-index-contrast (without incorporating metals) can be used to control \( Q_{\text{sca}} \) solely through the internal architecture of core-shell particles.

**Broader Impact:** This effort is establishing a wide-ranging, materials-agnostic fiber fabrication approach that can be used to create complex, multicomponent fibers with optical and electrical properties that can be utilized to create unique fiber based devices such as solar fabrics. The electronic and optical capabilities of these fibers can also be exploited as devices for stimulating and recording neuronal activity in humans to aid in the treatment of neurological disorders such as Parkinson’s disease. The complex nanoparticles created in these fibers can also be harvested for numerous other optical applications. On the fundamental side, this research offers a new paradigm for fluid-dynamic studies through the use of highly controlled environments for the observation of fluid instabilities involving multiple fluids co-flowing in hitherto unobtainable geometries and scales.

**Intellectual Merit:** IRG-II research seeks to understand the molecular mechanisms that govern the unique structure/property combinations of complex biological hydrogels and use this knowledge to create synthetic mimics with similar extraordinary properties. Using molecules engineered to contain a peptide sequence found in nucleoporins, this group has demonstrated that it is possible to use single amino acid substitutions to tune hydrophobic self-assembly in a manner that produces wide ranging mechanical properties. In addition, they have found that modulating the charge profile surrounding hydrophobic domains significantly impacts the physical and functional properties of hydrogels, including the permeability of diffusing substrates. This work has therefore established that the environment surrounding hydrophobic domains is a critical design parameter by which to fine-tune self-assembly and molecular recognition of hydrophobic domains within soft materials. In an attempt to mimic the hydrogel within the nuclear pore and create selective sorting abilities that would be useful to extract substrates that are not related to nuclear pore passage, such as contaminants of food, or water, this group has engineered curli fibers found in E. coli biofilms to display different peptides displaying negative, positive and neutral charges on their surfaces. Curli fibers are attractive as a platform scaffold for displaying peptides of interest and studying their resulting materials properties, since they are easily engineerable and low cost.

This IRG also reports on the synthesis of a new class of bio-inspired smart polymer materials with dynamically tunable crosslink junctions. The crosslinks are formed from metal-coordinating moieties that can be tuned from very stable to easily disassociated crosslinks by simply changing the nature of the metal involved in coordination. This means that the assembly of the polymer into hydrogels and the resultant mechanical properties can be directly controlled via by the kinetics of the network junctions.

In order to mimic the biological functions of aggrecan, the primary glycan-containing molecule of cartilage, members of this IRG have synthesized aggrecan bottlebrush mimics composed of a polypeptide backbone (L and D propargyl glutamates) modified with oligoethylene oxide side
chains. Preliminary results indicate that the equilibrium swelling and hydration properties of these synthetic polypeptide systems are depend strongly on the D or L isomer used to construct the chains and the resultant secondary structure. The mechanical properties of this series of gels have been investigated on the nanoscale by atomic force microscopy (AFM) indentation and on the macroscale by rheological studies.

**Broader Impact:** The fundamental knowledge and new materials developed within this IRG will lead to next generation materials with potentially wide engineering implications, such as the design of self-healing filtration systems for water and food purification, new antimicrobial coatings for implants, or cartilage substitutes with high durability and lubrication capacity. New insights into the origin of the extraordinary properties of biological hydrogels are also expected with an understanding of the interplay between three common motifs found in biological hydrogels: repeat domains, reversible crosslinking and glycosylation.

**Intellectual Merit:** IRG-III research seeks to discover the coupling mechanisms between oxygen defects and the transport of phonons, spin and charge at the interfaces of metal oxides. Using SrTiO$_3$ as an archetypal material for functional metal oxides, IRG-III researchers have established a theoretical framework for predicting the defect chemistry of SrTiO$_3$ with and without applied electric fields and predicted the polarization and electric enthalpy induced in a defect-free SrTiO$_3$ crystal upon applied electric field.

Resistance based random access memories (ReRAMs) are promising alternatives to current flash technology, but the durability of these devices is uncertain given a limited understanding of the switching mechanism. Members of this group have utilized Scanning Tunneling Microscopy (STM) to investigate the resistive switching behavior in TaO$_x$ and SrRuO$_3$ films. Results show that the switching mechanism in SrRuO$_3$ is different from TaO$_x$, and that oxygen defects play a vital role in SrRuO$_3$, providing new insights into the factors controlling switching. This group has also demonstrated that thermal conductivity can be controlled in oxide thin films by changing oxygen vacancy concentration. The thermal conductivity of SrCoO$_x$ films as a function of phase and film thickness was changed by a factor of 3 by electrochemical pumping of oxygen into/out of the films, with the latter suggesting a ballistic phonon transport mechanism. Nano-composites composed of a magnetic phase, (CFO, CoFe$_2$O$_4$) together with another phase of LSC or BSCF (La$_{0.8}$Sr$_{0.2}$CoO$_3$ or Ba$_{0.5}$Sr$_{0.5}$Co$_{0.8}$Fe$_{0.2}$O$_3$) have been used to explore the effects of hetero-interfaces on magnetism and oxygen reduction kinetics. It was demonstrated that the properties of the two phases are coupled due to a different strain state and crystal geometry making it possible to use an external field, like a magnetic field, to affect the properties of one phase, and indirectly affect those of the other phase. This IRG also carried out a systematic characterization of the effects of voltage cycling in Co/GdO$_x$/gate structures. It was found that devices first switch to a low-resistance state as the gate voltage is increased, and then back to a high resistance state at $V_g=+8$ V. This second resistive switching event was accompanied by abrupt changes in magnetic and optical properties and reversible changes in optical reflectivity could be observed between 0V and +3V.

**Broader Impact:** The research of this IRG has transformative implications for energy and information technologies. By better understanding the central role that oxygen defects play in the electrical, optical and magnetic properties of metal oxides at interfaces, this effort is expected to influence the next generation of emerging devices such as nanoionic and thermoelectric devices, fuel cells, and memristive and magnetoelectronic devices.

**Long-Range Plans/Issues:** This grant has only been up and running for about 9 months, no major changes to proposed plans and activities are anticipated in the near future.
2. PARTICIPANTS IN THE CENTER FOR MATERIALS SCIENCE AND ENGINEERING  
Nov. 1, 2014 TO October 31, 2015

Senior Investigators in bold font  
Participants in Sections I and II included in Appendix B  
† Bush Materials Science and Engineering Building (Bldg. 13) occupant  
* User of CMSE Shared Facilities

I. Faculty Receiving MRSEC Support (sorted by academic department)

<table>
<thead>
<tr>
<th>Name</th>
<th>Department</th>
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<tbody>
<tr>
<td>Doyle, Patrick S.</td>
<td>Chem. Eng.</td>
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<tr>
<td>Johnson, Jeremiah A.</td>
<td>Chemistry</td>
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<td>Surendranath, Yogesh</td>
<td>Chemistry</td>
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<tr>
<td>Leeb, Steven</td>
<td>EECS</td>
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<tr>
<td>Anikeeva, Polina</td>
<td>Mat. Sci. &amp; Eng.</td>
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<td>Beach, Geoffrey S. D.</td>
<td>Mat. Sci. &amp; Eng.</td>
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<tr>
<td>Belcher, Angela</td>
<td>Mat. Sci. &amp; Eng.</td>
</tr>
<tr>
<td>Fink, Yoel †</td>
<td>Mat. Sci. &amp; Eng.</td>
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<td>Holten-Andersen, Niels</td>
<td>Mat. Sci. &amp; Eng.</td>
</tr>
<tr>
<td>Ross, Caroline A.</td>
<td>Mat. Sci. &amp; Eng.</td>
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<tr>
<td>Rubner, Michael †</td>
<td>Mat. Sci. &amp; Eng.</td>
</tr>
<tr>
<td>Tuller, Harry L. †</td>
<td>Mat. Sci. &amp; Eng.</td>
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<td>Johnson, Steven</td>
<td>Mathematics</td>
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<tr>
<td>Yildiz, Bilge</td>
<td>Nuclear Sci. &amp; Eng.</td>
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<tr>
<td>Checkelsky, Joseph G.</td>
<td>Physics</td>
</tr>
<tr>
<td>Joannopoulos, John</td>
<td>Physics</td>
</tr>
<tr>
<td>Soljačić, Marin</td>
<td>Physics</td>
</tr>
</tbody>
</table>

Subawards
Abouraddy, Ayman (U. of Central Florida) Optics and Photonics
II. Affiliated Faculty, Not Receiving MRSEC Support (sorted by academic department)

Internal

Baldo, Marc †*

Bulovic, Vladimir †*

Fonstad, Clifton †

Kong, Jing †*

Orlando, Terry †

Warde, Cardinal †

Dresselhaus, Mildred †*

Allanore, Antoine †*

Carter, W. Craig †

Ceder, Gerbrand †*

Chiang, Yet-Ming †*

Fitzgerald, Eugene †*

Gradečak, Silvija †*

Grossman, Jeffrey †*

Hu, Juejun †*

Kimerling, Lionel †*

Ortiz, Christine †*

Thompson, Carl †*

Shao-Horn Yang †*

Ashoori, Raymond †*

Benedek, George †

Gedik, Nuh †*

Jarillo-Herrero, Pablo †*

Internal

Lozano, Paulo

Martinez-Sanchez, Manuel

Wardle, Brian

Lechtman, Heather

Boyden, Edward

Jasanoff, Alan

Gvoight, Christopher

Anderson, Daniel

Blankschtein, Daniel

Gleason, Karen

Hatton, Trevor Alan

Jensen, Klavs

Langer, Robert

Myerson, Allan

Roman, Yuriy

Rutledge, Gregory

Strano, Michael

Tisdale, William

Trout, Bernhardt

Wang, Daniel

Bawendi, Mouni

Buchwald, Stephen

Faculty and Staff Level Users of CMSE Shared Experimental Facilities (sorted by affiliation)

Internal

Lozano, Paulo

Martinez-Sanchez, Manuel

Wardle, Brian

Lechtman, Heather

Boyden, Edward

Jasanoff, Alan

Gvoight, Christopher

Anderson, Daniel

Blankschtein, Daniel

Gleason, Karen

Hatton, Trevor Alan

Jensen, Klavs

Langer, Robert

Myerson, Allan

Roman, Yuriy

Rutledge, Gregory

Strano, Michael

Tisdale, William

Trout, Bernhardt

Wang, Daniel

Bawendi, Mouni

Buchwald, Stephen

Chemistry

Chemistry
2. PARTICIPANTS IN THE CENTER FOR MATERIALS SCIENCE AND ENGINEERING
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Faculty Level/Staff Users of CMSE Shared Experimental Facilities (continued)
Cummins, Christopher Chemistry
Dincă, Mircea Chemistry
Lippard, Stephen Chemistry
Nelson, Keith Chemistry
Pentelute, Bradley Chemistry
Schlau-Cohen, Gabriela Chemistry
Swager, Timothy Chemistry
Van Humbeck, Jeffrey Chemistry
Bourouiba, Lydia Civil and Environmental Eng.
Buehler, Markus Civil and Environmental Eng.
Buyukozturk, Oral Civil and Environmental Eng.
Germaine, John Civil and Environmental Eng.
Jennings, Hamlin Civil and Environmental Eng.
Kroll, Jesse Civil and Environmental Eng.
Ochsendork, John Civil and Environmental Eng.
Pellenq, Roland Civil and Environmental Eng.
Reis, Pedro Civil and Environmental Eng.
Ulm, Franz-Josef Civil and Environmental Eng.
Whittle, Andrew Civil and Environmental Eng.
Matusik, Wojciech Comp. Sci. & Artificial Intelligence Lab
Bosak, Tanja Earth, Atmos. & Planetary Sci.
Cziczo, Daniel Earth, Atmos. & Planetary Sci.
Evans, James Earth, Atmos. & Planetary Sci.
Ono, Shuhei Earth, Atmos. & Planetary Sci.
Akinwande, Akintunde EECS
Berggren, Karl EECS
del Alamo, Jesus EECS
Englund, Dirk EECS
Fisher, Peter EECS
Hagelstein, Peter EECS
Kassakian, John EECS
Palacios, Tomas EECS
Schmidt, Martin EECS
Voldman, Joel EECS
Edelman, Elazer Health Science and Technology Program
Bhatia, Sangeeta Institute for Medical Eng. and Science
Ghorohgchian, Paiman Koch Inst. for Integrative Cancer Research
Hart, Anastasios Lab fro Manufacturing & Productivity
Agarwal, Anuradha Materials Processing Center
Michel, Jurgen Materials Processing Center
Cima, Michael Mat. Sci. and Eng.
Demkowicz, Michael Mat. Sci. and Eng.
Eagar, Thomas Mat. Sci. and Eng.
Gibson, Lorna Mat. Sci. and Eng.
Harris, Daniel Mat. Sci. and Eng.
Irvine, Darrell Mat. Sci. and Eng.
Olivetti, Elsa Mat. Sci. and Eng.
Oxman, Neri Mat. Sci. and Eng.
Sadoway, Donald Mat. Sci. and Eng.
Schuh, Christopher Mat. Sci. and Eng.
## 2. PARTICIPANTS IN THE CENTER FOR MATERIALS SCIENCE AND ENGINEERING  
Nov. 1, 2014 TO October 31, 2015

**Faculty Level/Staff Users of CMSE Shared Experimental Facilities (continued)**

<table>
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<tr>
<th>Name</th>
<th>Department</th>
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<tbody>
<tr>
<td>Smith, Dave</td>
<td>Mat. Sci. and Eng.</td>
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<td>Ram, Rajeev</td>
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## 2. PARTICIPANTS IN THE CENTER FOR MATERIALS SCIENCE AND ENGINEERING

**Nov. 1, 2014 TO October 31, 2015**

### External Academic

<table>
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<th>Name</th>
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<td>Li, Lele</td>
<td>Boston Children's Hospital</td>
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<td>Masoumi, Nafiseh</td>
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<td>Liu, jilei</td>
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<td>Lin, Hongtao</td>
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<td>Helbling, Angela</td>
<td>Woods Hole Ocean. Inst., Geo. &amp; Geophys.</td>
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2. PARTICIPANTS IN THE CENTER FOR MATERIALS SCIENCE AND ENGINEERING
   Nov. 1, 2014 TO October 31, 2015

External Commercial
Carlin, Andrew 4 Power LLC
Gross, Martha Ambri, Inc.
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Lipp, Michael Civitas Therapeutics, Inc.
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Pijpers, Joep Sun Catalytix
Kane, Derrick Ubiquitous Energy

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State University
Universidad Metropolitana San Juan, Puerto Rico
U. Estadual de Campinas Sao Paulo, Brazil
### 3. COLLABORATORS WITH THE CENTER FOR MATERIALS SCIENCE AND ENGINEERING OVER THE LAST 48 MONTHS
**NOVEMBER 1, 2014 TO JULY 31, 2015**

<table>
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<tr>
<th>Collaborator</th>
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<th>E-mail</th>
<th>Field of Expertise</th>
<th>Group Affiliation</th>
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<td>CREOL, University of Central Florida</td>
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<td>RG-I</td>
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<td>Neuroprosthetics</td>
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<td>Nave, Jean-Christophe</td>
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<td>Semi-Lagrangian methods</td>
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<td>Segev, Mordechai (Mo)</td>
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<td>Nanoparticle fabrication and characterization</td>
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<tr>
<td>Shain, William</td>
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<td><a href="mailto:william.shain@israelchildrens.org">william.shain@israelchildrens.org</a></td>
<td>Biomarker quantification in fiber-neural tissue</td>
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<td>Soin, Fabien</td>
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<td>Photonic devices and fiber technology</td>
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<td>Stone, Howard</td>
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<td>Fluid motions dominated by viscosity</td>
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<td>Knock outs for aggrecanase and collagenase</td>
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<td>Gilson, Matthew</td>
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<td>Glycochemistry</td>
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<td>Material properties of protein-based biological polymers</td>
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<td>Magnetic tweezers</td>
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<td>Traumatic knee injuries</td>
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<td>Coey, Michael</td>
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<td>Mossbauer measurements of magnetic perovskites</td>
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<td>Density functional theory calculations</td>
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<td>Inoue, Mitsuuru</td>
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<td>Magnetism and magnetic materials</td>
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<td>Crisnell, Reim</td>
<td>National Institute of Standards and Technology</td>
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<td>Experimental condensed matter physics</td>
<td>Seed-3</td>
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4. CENTER STRATEGIC PLAN

Overview: MIT has an exceptionally strong and wide-ranging effort in materials science and engineering that cuts across eleven different academic departments in the schools of science and engineering (about 200 faculty and senior staff). The MIT MRSEC, locally known as the Center for Materials Science and Engineering (CMSE), is a cross-school interdisciplinary center that plays the critical role of bringing this diverse materials community together by encouraging and supporting collaborative research and innovative educational and industrial outreach programs. The clear and important mission of the MIT MRSEC is to encourage high impact, fundamental research and education in the science and engineering of materials in support of existing and emerging technologies that will address the current and future needs of society. To accomplish this mission, CMSE enables collaborative interdisciplinary research among MIT faculty and the researchers of other universities, industry, and government laboratories. An important goal is to keep industry, government laboratories, and other universities aware of the latest developments and discoveries from within the center and to facilitate technological developments and knowledge transfer that will impact society and the economy. Another key objective is to develop state-of-the-art shared facilities that provide and maintain critically enabling instrumentation for CMSE MRSEC investigators and, at the same time, serve as an important resource to the broader MIT and US materials community. The latter objective is realized by participation in the MRSEC program established Materials Research Facilities Network program (MRFN). Underlying all of these goals is a strong motivating conviction that the complex scientific problems facing this nation are best addressed by engaging a highly diverse talent pool.

Research: The overarching objective of the MIT MRSEC research program is to support collaborative, interdisciplinary research that addresses important complex problems not easily solved without a diverse team of researchers from different fields. This objective is realized through the support of interdisciplinary research groups (IRGs), seed projects, and shared experimental facilities (SEFs). All IRGs share common elements that are critical to their success including fully integrated theory and modeling efforts and advanced materials synthesis, processing and characterization capabilities. At the heart of each IRG is a set of clearly articulated fundamental hypotheses aimed at resolving key scientific questions about an important emerging area of materials science. In IRG-I, for example, the focus is on detailed fundamental studies of in-fiber fluid instabilities in multiple fluid systems. IRG-II, on the other hand, focuses on unraveling the multi-faceted interplay of structural elements in complex biological hydrogels. IRG-III focuses on a key unresolved issue in materials with oxygen defects: namely, what coupling mechanisms exist between oxygen defects and the transport of phonons, spin and charge at the interfaces of complex oxides. To ensure that all MRSEC supported research programs deliver the highest possible scientific and technological impact, CMSE utilizes an extensive review process involving internal and external evaluation of its programs. Regular meetings of the internal advisory committee (IAC) are used to ensure that IRG, SEF, and educational outreach leaders understand and share a common vision for the center. The Science and Engineering External Advisory Board (SEEAB) provides an outside perspective on the impact of MRSEC activities. This committee is composed of leaders of industrial, academic and government laboratories that support major efforts in long-range materials research and engineering. Important metrics utilized to evaluate research programs include, for example, number, quality, and impact of peer-reviewed publications (with an emphasis on multi-PI papers), level and effectiveness of multi-investigator collaborative activities; engagement of post-docs and graduate and undergraduate students in research; and effectiveness of knowledge transfer and integration of outreach activities.

Education: The MIT MRSEC offers a wide variety of educational outreach programs including programs directed at middle and high school students, K-12 teachers, women and minorities,
undergraduates, and graduate students. Over the years, the MIT MRSEC has established strong collaborative relationships with local middle and high school systems and community colleges as well as universities in Puerto Rico. These successful relationships are leveraged to create finely-tuned programs that achieve their important outreach goals and objectives. The center’s educational goal is to provide a portfolio of effective and innovative educational outreach programs that are integrated into its research activities and benefit from wide participation of MIT faculty and students. In all of CMSE’s programs, specific measures are in place to promote and enhance diversity within each participant pool. Assessment of the educational outreach programs against their objectives are accomplished by carefully crafted entrance and exit surveys and, where possible, by tracking participant activities after completion of the programs. Another important metric is the level of subsequent involvement/collaborative interactions participants have with the center. MRSEC supported students and post-docs are encouraged to participate in multiple center outreach programs to gain teaching experience, mentoring and supervising skills, and exposure to a diverse range of cultures and cultural experiences. A strong center-driven post-doc mentoring program involving collaborative activities with multiple MIT departments is used to advance the careers of these aspiring young researchers with a focus on academic, government lab and industrial career paths.

**Diversity:** The MIT MRSEC has a history of encouraging traditionally underrepresented minority groups and women to participate in materials research and education through its educational outreach programs, dedicated sponsorship of graduate research assistants, special junior faculty programs and efforts to coordinate CMSE activities with other MIT programs and departments. CMSE’s diversity goals include three key elements: 1) implementation of strategies to increase the diversity of participants in the existing education programs, 2) development of new outreach programs that specifically target underrepresented minority groups, and 3) initiation and execution of collaborations with other units at MIT that are working to address the diversity challenge in science and engineering. One key metric for assessing the impact of these activities is the number of women and minorities participating in CMSE programs. However, it is not sufficient to simply increase numbers. Thus, an important goal is to establish a support infrastructure that ensures that program objectives are realized. CMSE works closely with assigned faculty members from partner organizations to monitor the progress of participants and better understand their needs. Close relationships of this type also help track the subsequent progress of participants. At the faculty level, the MIT MRSEC has implemented a number of new programs aimed at helping departments recruit and retain underrepresented minorities and women. MIT is fully committed to addressing the diversity issue and has put in place new programs that directly couple with the objectives of the MIT MRSEC.

**Knowledge Transfer:** MIT has a long-standing successful history of converting the knowledge gained through fundamental studies into important technologies that benefit the human experience across the globe. The MIT MRSEC has made important contributions to this legacy including providing the fundamental knowledge base that underlies a number of successful start-up companies and new technologies. This is accomplished by working closely with two key organizations at MIT: MIT’s Materials Processing Center (MPC) and Industrial Liaison Program (ILP). These organizations work directly with MRSEC supported faculty and the MRSEC director to make connections to industry and explore how the basic science generated with the MRSEC program can be utilized to enhance existing technologies or to establish new technologies. In addition, center driven international collaborations and the collaborations between IRG researchers and scientists at other universities and national and industrial laboratories provide excellent opportunities for knowledge transfer and exchange.
5. IRG-I: HARNESSING IN-FIBER FLUID INSTABILITIES FOR SCALABLE AND UNIVERSAL MULTIDIMENSIONAL NANOSPHERE DESIGN, MANUFACTURING, AND APPLICATIONS

Senior Investigators: Yoel Fink and Marin Soljačić (co-leaders), Ayman Abouraddy (UCF), Polina Anikeeva, John Joannopoulos, and Steven Johnson

Postdoctoral Associates: 4   Graduate Students: 11   Undergraduate Students: 7

Research Goals: IRG-I focuses on the study and development of unique structures based on the ability to harness a newly discovered nonlinear fiber fluid instability to generate regularly sized nanospheres in fibers. The main objectives are to introduce a new materials-agnostic fabrication approach for nanospheres of arbitrary geometry and dimensions, and to develop a new paradigm for fundamental fluid-dynamic studies offering a highly controlled environment for the observation of fluid instabilities involving multiple fluids co-flowing in hitherto unobtainable geometries and scales.

Highlights of Research Accomplishments:

Processing Fundamentals: During this reported period, Fink and Joannopoulos have focused on harnessing non-linear fluid instability effects in fibers to produce in-fiber capillary breakup of localized domains in an otherwise continuous fiber and to demonstrate the ability to generate millions of discrete devices in a fiber. To do so one has to overcome what may appear to be a fundamental roadblock, how could certain fluid domains breakup (semiconductors) while other (metals) remain continuous. To that end, this project is now focused on developing the concept of selective and coherent in-fiber capillary breakup. Specifically, three approaches with increasing spatial control and material selectivity were pursued: the Tomotika and isothermal approach, and the thermal gradient “dripping faucet”. Laser induced breakup was also applied to low temperature and high temperature materials systems.

The main accomplishments on this project in the past year may be summarized as follows:

1. Demonstrated the ability to produce integrated in-fiber electronics through selective fluid instabilities – “self-assembly” of optoelectronic devices through selective break up where the semiconducting core underwent disintegration to a periodic array of spheres while the conductive electrodes were kept continuous and connected to the semiconducting spheres. Very high device density (>100,000 devices per meter of a fiber) is readily achieved through a one-step assembly process, as shown in the Figure 1.

2. Developed a laser-induced capillary breakup setup and experimentally demonstrated silicon sphere generation. The laser setup consists of two lasers with different wavelengths, one of which is mainly absorbed by the fiber cladding and other that is mainly absorbed by the fiber core. Thus, a high controllability and accuracy of the temperature profile is obtained.

A numerical model was set up [1] to show that varying fiber feed speed gives different size particles roughly in line with a simple dimensional model. However, the simulations were much smaller in length scale than reality and the viscosities were also unrealistic. Now, a large-scale parallel Stokes solver has been developed by the Johnson group that scales up to the experimental parameter regimes. The solver takes advantages of PETSc libraries in implementing both parallelization and linear sparse solvers. One realistic-scale simulation typically takes about 3,000 cpu-hours. Results of the capillary breakup are roughly similar to experimental observations, although an exact match is impossible due to large experimental
uncertainties in the spatial temperature as well as the values of viscosities and interfacial tension.

Figure 1. Evolution and results of break up in fibers. (a) Illustration of break up process of a fiber that contains three cores without the correct design for selective break up. The three cores undergo break up at the hot zone of a furnace (illustrated by the red light). Spheres form at all the cores, without coherency between the components. (b) Illustration of the selective break up process. A fiber that is placed in a furnace or on a hot plate is heated and the inner core undergoes break up while the electrodes stay continuous - forming a self assembled spherical photodetectors inside the fiber.

(c) Optical micrograph of a fiber designed to undergo selective break up – prior to break up. (d) Optical micrograph of a fiber during the onset of break up process – the inner core develops instability, while the electrodes are kept continuous. (e) Optical micrograph of a fiber after break up with chalcogenide glass spheres, diameter of 200µm connected to continuous electrodes.

In Figure 2, a simulation result of the capillary breakup of a Si-SiO₂ fiber fed into a laser spot is shown. Enhancement of the numerical methods, in collaboration with Prof. J.C. Nave at McGill University is sought after as well, to employ semi-Lagrangian methods (which provide both enhanced spatial resolution and performance) [2].

At the same time, a key goal is to use the numerics to help develop and validate a quantitative semianalytical model—such a model allows both efficient parameter exploration and also can yield insights into the nature of the physics. Within linear perturbation regime and under the assumption of slowly varying viscosity, \( \frac{d \mu(z)}{dz} \ll \frac{\mu(z)}{\lambda} \), the Johnson group proposed a local growth rate formula for the interface, \( \delta r(z, t + dt) = \int \delta \rho(k, t) e^{ikz} e^{i\sigma(k, z) dt} \), where \( \sigma(k, z) \) is the local Tomotika growth rate. By taking the limit of \( dt \to 0 \), the differential equation for the Fourier mode evolution can be obtained:

\[
\frac{\partial f(k, t)}{\partial t} = \int dk' \sigma(k', k - k') f(k', t) \quad \text{and} \quad f(k, t) = e^{i \int dk' \sigma(k', k - k') t} f(k, 0).
\]

The next step is to validate this approach with numerical simulation and incorporate the “end” of the fiber in a

Figure 2. Simulation results to show the capillary breakup of a Si-SiO₂ fiber fed into a laser spot. The core radius is 20µm and the feed speed is 2µm/s. The laser spot, hence the high temperature region is for \( z \leq 130 (\ast 20\mu m) \).
manner similar to marginal stability analysis [3,4] (which combines Tomotika with an "end" to quantitatively predict droplet formation from the retraction of the end).

Applications to Neuroscience: Traumatic injury to the peripheral nervous system (PNS) often leads to the significant, often complete lost of motor and sensory functions in the corresponding limb. The treatment of PNS trauma is currently limited due to the poor regenerative ability of neural tissue at the site of injury. Autografts (nerve transplants from a different part of the body) currently represent the “gold standard” of treatment, however their invasiveness and only partial restorative ability motivate investigation of alternative approaches. Synthetic scaffolds hold promise to eventually replace nerve autografts for PNS repair in the clinic. These scaffolds should integrate with severed nerves and expedite the reconnection and regeneration of peripheral neural tissue in patients suffering from loss of motor functions, spasticity, and pain following a trauma.

A number of physical cues including microscale topography and electrical stimulation have been shown to improve the rate of axonal regeneration both in vitro and in vivo. Despite these indications, the vast majority of neural scaffolds are passive structures with cylindrical geometry. The Anikeeva group hypothesizes that the materials processing is a limitation in scaffold design and is applying the fiber-drawing methods developed within this IRG to create active optoelectronic neural scaffolds with tunable topographic features.

Figure 3 illustrates the incorporation of grooved topography into the preform, a macroscopic template of a fiber. Following thermal drawing the features of the fiber are reduced by up to 200 times, and a variety of geometries can be produced. The Anikeeva group has tested fiber-based scaffolds with round, square and grooved inner geometries in vitro using sensory dorsal root ganglia (DRGs) as a model system for peripheral neural tissue (Figure 4). The initial findings indicate that a grooved geometry improves the axonal growth by up to 2 times, which may be correlated to the alignment of the developing processes and cell bodies along the topographic features.

In addition to studying the role of scaffold geometry, a study of the influence of neural activation on the axonal growth was performed. By employing optically-sensitive DRGs that express a blue light-gated ion channel Channelrhodopsin 2 (ChR2), it was identified that neural stimulation with frequencies of 5-50 Hz for 0.5-4 hrs can accelerate axonal growth by over 3 fold [5]. The
next step is developing the further generation of neural scaffolds that would combine the
topographic features with optical stimulation capabilities and would also integrate electrodes for
monitoring of neural activity during axonal growth and development.

Nanoparticle Development: Metallic nanoparticles are known for their strong but narrow
visible-range extinction peaks due to plasmon resonance. By normalizing optical extinction to
particle volume ($\sigma_{ext}/V$) over a broad range of incoming wavelengths, extinction coverage
produced by the smallest possible particle can be maximized over the entire visible range.

Prior theoretical research demonstrates that oblate ellipsoid nanoparticles are able to extinguish
visible light normalized to nanoparticle size more efficiently than almost any other shape. It has
also been demonstrated that a fundamental limit to extinction efficiency can be established
based solely on material permittivity, and that silver is the best candidate for this for most of the
visible range [6]. Indeed, the theoretical upper bound on oblate silver nanoplates’ $\sigma_{ext}/V$ exceeds
current technologies such as titanium dioxide macropowders and engineered gold and silica
nanoparticles by almost a whole order of magnitude [7].

Soljacic, Johnson, and Joannopoulos report (manuscript in preparation) that this has now
been experimentally realized and verified. Nanoparticles were synthesized and tailored to three
common visible bandwidth windows: 400-600nm, 600-800nm, and 400-800nm. The window of
extinction was controlled by altering the aspect ratios of the nanoparticles, which in turn dictate
their optical properties. Experimental results were compared to a 'maxmin' theoretical upper
limit that sought to find the ideal distribution of nanoparticle aspect ratios that would produce the
most volume efficient “worst case” obscuring ability for each individual wavelength over the
given wide bandwidth. Individual aspect ratios were precisely measured using TEM imaging,
and UV-Vis spectroscopy was used to calculate $\sigma_{ext}/V$. To tailor nanoparticles to obscure over
the 400-800nm window, the two other colloids were mixed together. High efficiencies were
achieved, up to 100% over the entire visible range (see Figure 5 below).

To date, tailoring the optical scattering efficiency $Q_{sca}$ (defined as the ratio of the scattering to
geometric cross sections) from particles has relied on either changing their size or refractive
index. Realizing high $Q_{sca}$, as necessary, for example, in optical coatings to achieve opacity in
thin layers without absorption, typically necessitates increasing the refractive index, an
approach fundamentally limited by naturally available materials. Abouraddy and Fink (in
collaboration with Prof. A. Dogariu, UCF) have shown that multilayer dielectric particles with
controlled radial structure and high refractive-index-contrast (without incorporating metals)
enable rational control over $Q_{sca}$ solely through the internal architecture. Calculations of $Q_{sca}$ at
a wavelength $\lambda = 532$ nm for a core-shell particle of fixed radius $a = 500$ nm (polymer-core and
glass-shell particle), reveal a modulation in $Q_{\text{sca}}$ while varying the core radius $r_c$ between two limits: an all-glass particle ($r_c = 0$) and an all-polymer particle ($r_c = a$). By tuning an internal geometric degree of freedom, $Q_{\text{sca}}$ may be varied below or above that of equi-sized uni-material particles made of either of the constitutive materials. These predictions have now been confirmed by examining particles having three different core-shell ratios, structures A ($r_c = 0$ nm), B ($r_c = 325$ nm), C ($r_c = 400$ nm) and selected to confirm that tuning $r_c$ can reduce or enhance $Q_{\text{sca}}$. Critically, to isolate the effect of the internal particle structure on $Q_{\text{sca}}$ and eliminate the impact of particle-particle interactions, measurements on a single particle have been realized by constructing a dark-field setup in which the particle is excited by an evanescent optical field (532-nm-wavelength laser beam) through a prism. Scattered light is detected using a near-field optical probe scanning across a plane situated at a height $\approx 2 \, \mu m$ above the particle. This constitutes the first measurement of the scattering phase function for a single photonic particle at a visible wavelength.

**Figure 5.** (a) Measured aspect ratio distribution of synthesized nanoparticles compared to theoretically optimized distribution. Larger aspect ratios are optimal for longer wavelengths, whereas the broad distribution of aspect ratios provides strong response over a broad wavelength window. (b) The synthesized nanoparticles’ $\sigma_{\text{ext}}/V$ spectra closely approach the highly optimized theoretical limits (dashed lines). 400-600nm particles (blue) are able to achieve 86% of the theoretical maximum while 600-800 (red) particles achieve 67%. (c) By mixing the two, optimal (100% of the theoretical maximum) 400nm-800nm broadband extinction is achieved (purple).

**References**

5. IRG-II: SIMPLE ENGINEERED BIOLOGICAL MOTIFS FOR COMPLEX HYDROGEL FUNCTION

Senior Investigators: Katharina Ribbeck and Patrick Doyle (co-leaders), Bradley Olsen, Niels Holten-Andersen, Jeremiah Johnson, Alan Grodzinsky, Paula Hammond, and Timothy Lu

Postdoctoral Associates: 4  Graduate Students: 7  Undergraduate Students: 2

Long-Term Research Goals and Intellectual Focus: The goal of this IRG is to gain quantitative insight into, and predictive capability of, the molecular mechanisms that govern the unique structure and property combinations of complex biological hydrogels. This fundamental knowledge will be used to guide the synthesis, fabrication and evaluation of next generation materials with potentially wide engineering implications, such as the design of self-healing filtration systems for water and food purification, new antimicrobial coatings for implants, or cartilage substitutes with high durability and lubrication capacity. This IRG is divided into three interconnected thrusts. Its thrust efforts are designed to investigate the molecular chemistry and structure property relationships of repeat domains, reversible crosslinking and glycosylation, and use the resulting knowledge to synthesize bio-inspired hydrogels that strategically contain all three elements. Thrust 1 focuses on the well-defined repetitive domains from the nuclear pore complex hydrogel to study their role for the filtration properties of biological hydrogels. Thrust 2 utilizes tools from chemical engineering to identify how specific dynamics and chemistry of reversible crosslinks relate to key bulk material properties such as viscoelasticity, self-healing and durability. Building on this knowledge, prioritized types of crosslinking to generate hydrogels with controlled behavior will be developed. Thrust 3 seeks to determine the biological function of polymer-associated glycan chains in regulating the biomechanical and filtration properties of hydrogels.

Highlights of Research Accomplishments:

Thrust 1: Engineering repeat domains with varying arrangements of charge and repeat length. To identify those parameters of the repeat domains that are relevant for achieving selectivity in hydrogels, the Ribbeck lab has begun to engineer peptides modeled after nucleoporin-like repeats, which are composed of terminal hydrophobic FSFG domains commonly found in nucleoporins with a hydrophilic linker sequence AXAAXA. The character of the domains has been varied, and the charge has been changed and reversed. Using these peptides, the data show that single amino acid substitutions that modulate the charge and biochemistry around FG domains can be used to tune hydrophobic FG self-assembly to form diverse materials ranging from non-cohesive solutions to hydrogels with a stiffness of $10^4$ Pa. Moreover, the data show that electrostatic manipulations can be used to enhance or shield hydrophobic interactions to control permeability of diffusing substrates within gels containing hydrophobic moieties. Together, the results so far show that modulating the charge profile surrounding hydrophobic domains significantly impacts the physical and functional properties of hydrogels. By establishing the environment surrounding hydrophobic domains as a critical design parameter, this work has identified an effective mechanism by which to fine-tune self-assembly and molecular recognition of hydrophobic domains within soft materials. This work is currently in preparation for submission. Moving forward, this prototypic peptide system will be judiciously combined with the crosslinking technology from Thrust 2, and the glycopeptide chemistry from Thrust 3 to explore, and begin to regulate, the unique structure and property combinations found in complex biological hydrogels.

The hydrogel within the nuclear pore is optimized for sorting cellular components, but it would also be desirable to tailor the permeability of the hydrogel to extract substrates that are not related to nuclear pore passage, such as contaminants of food, or water. Biofilms are natural hydrogels composed of extracellular polymeric substances and cells. The extracellular matrix of
**E. coli** biofilms contain proteinaceous fibers called curli, which are composed of the CsgA protein. Curli fibers have been engineered to display heterologous peptides by fusing them to CsgA [1]. Peptide synthesis methods and phage display for the formation of hydrogels with nuclear pore repeat domains are challenging. Curli could serve as a platform scaffold for displaying peptides of interest and studying their resulting materials properties, since they are easily engineerable and low cost. Moreover, synthetic gene regulation over engineered curli fiber assembly could enable the creation of living materials with tunable permeability. Preliminary results from the Lu lab show that curli fibers can be assembled from a CsgA protein fused to nuclear pore peptides incorporating arginine (R-peptides). Three types of flexible linkers between CsgA and the peptides were tested. Interestingly, the morphology of the fibers changed compared to wild-type curli as they appeared to adopt a more linear configuration, possibly because of charge repulsion. Different peptides displaying negative, positive and neutral charges are currently being incorporated in the curli fibers and their effects on materials properties will be investigated with rheology and charged particle tracking [2].

**Figure 1.**

a. Amino acid sequence of fusion protein constructs with R-peptides and 3 different linkers between CsgA and R-peptides: either two GGGS flexible linkers, one GGGS linker or none b. Crystal violet staining of biofilms comprised of *E. coli* strains encoding a CsgA-R-peptide fusion protein. Expression and assembly of curli fibers is induced by addition of a small molecule, anhydrotetracycline (aTc). The R-peptide strain with one linker exhibited the most robust biofilm formation, although 1.5 times less than a CsgA wild-type under aTc induction. c. Transmission Electron Microscopy (TEM) of curli fibers that are fused to R-peptides with one flexible GGGS linker compared with wild-type curli. Mag x10000

Soft matter systems developed in this project demand mechanical measurement techniques that require only small quantities of samples (~microliters) and can measure spatially varying material properties. During this research period, Doyle has established two techniques based on particle-tracking. The first is passive microrheology wherein Brownian motion of beads drives their random motion in the fluid. Autocorrelation of particle motions is related to material
properties. A new student working on the project adapted existing particle-tracking techniques and developed code to extract linear viscoelastic moduli (G' and G'') from the trajectories of beads embedded in a soft material. Aqueous solutions of high molecular weight PEO (4% MW=900,000 solutions) were studied as a test case. Sample rheological data is shown in Figure 2. Using methods developed by the Doyle group to account for static error in the measurements, data over 3 decades of frequency and stress were obtained. The Doyle group also put in place a magnetic tweezer technique for measuring nonlinear microrheological properties of complex fluids. The apparatus consists of a soft magnetic core around which an electromagnetic coil is wound. The geometry of the core tip generates large magnetic field gradients, which in turn leads to large forces exerted on magnetic beads. Initial calibration of the device suggests that forces up to ~10nN can be locally exerted on beads. This device is capable of measuring nonlinear properties of materials, such as shear rate dependent viscosity or stress induced yielding of soft gels.

![Figure 2. Viscoelastic moduli of PEO obtained from passive particle tracking microrheology.](image)

**Figure 2.** Viscoelastic moduli of PEO obtained from passive particle tracking microrheology.

![Figure 3. Early data demonstrating proof of concept in the bio-inspired polymer material design approach. By assembling metal coordinating polymer (MCP) networks via binding onto metal nanoparticles, self-assembly into nanoscopic crosslink structures or traditional covalent crosslink chemistry (a) visco-elastic mechanics (b) can be controlled directly via metal-coordinate crosslink dynamics (c).](image)

**Figure 3.** Early data demonstrating proof of concept in the bio-inspired polymer material design approach. By assembling metal coordinating polymer (MCP) networks via binding onto metal nanoparticles, self-assembly into nanoscopic crosslink structures or traditional covalent crosslink chemistry (a) visco-elastic mechanics (b) can be controlled directly via metal-coordinate crosslink dynamics (c).

**Thrust 2:** The primary goal of this collaboration between Johnson and Holten-Andersen is to establish a new class of smart polymer materials with controllable network junctions by utilizing
bio-inspired metal-coordinating polymers (MCPs) capable of self-assembly into and onto nanostructures with tunable properties (see Figure 3). Specifically, by decorating polymer backbones with ligands known to self-assemble into well-defined metal-coordinated geometric shapes or with ligands known to bind onto metal nanoparticles with tunable adhesive energy, this collaboration has already led to the assembly of stimuli-responsive supra-molecular structures at polymer network junctions upon the simple addition of a metal ion or metal nanoparticle [3,4] (see Figure 3a). With polymer material assembly now directly controlled via network junction kinetics and material mechanics dependent on measurable network junction structural dynamics, this effort is quickly building an ideal platform upon which to explore the function of simple engineered bio-inspired motifs in complex hydrogel function such as self-healing and controllable energy dissipation. The functional applications of these materials are largely unexplored but predicted to be widespread.

In this initial period of the MRSEC award, the work of Olsen was focused on understanding the relationships between macroscopic mechanical responses in gels and the microscopic chemical bond dynamics that influence these responses. Using forced Rayleigh scattering (FRS) as a technique to measure diffusion in hydrogels across length scales from 100’s of nm up to several microns, it was discovered that gels can exhibit super-diffusive behavior. This behavior was captured by a simple two-state model for gel dynamics, where molecules exist in bound and unbound states with slow and fast diffusivities, respectively. In this project, the goal is to apply this model to understand the dynamics in a metal coordinated gel composed of a polyacrylamide polymer with histidine side chains. The histidines coordinate to many transition metals, forming physical bonds in the gel. Using nickel as a metal, it was possible to prepare optically transparent gels and measure diffusion, observing two characteristic relaxation times consistent with the predictions of the two-state model. Fitting to the model allowed an estimation of constants such as the diffusivity and the rate of transition between the bound and unbound state. The rate constant of unbinding provides a powerful predictor of mechanical response, allowing rheology curves as a function of concentration to be collapsed onto a single master curve. However, it is not clearly relatable to a molecular parameter of the physical bond. Therefore, bond exchange measurements are currently performed with the aim of elucidating the relationship between this empirical molecular dissociation rate and the microscopic bond dissociation rate. In addition, these materials were shared with the group of Holten-Andersen, who is working to analyze their mechanical properties with a variety of different coordination metals.

The goal of Thrust 3 is to explore the biological functions of polymer-associated glycan chains in regulating the material properties of hydrogels, using aggrecan, the primary glycan-containing molecule of cartilage, as a model system. To investigate the role of glycans in hydrogel properties aggrecan bottlebrush mimetics will be generated and the role glycan density, length and charge on the mechanical and permeability properties of hydrogels formed with these mimetics analyzed. This thrust represents an integration of synthetic, physicochemical, and biomechanical characterization using the unique toolsets from the Hammond, Grodzinsky and Doyle laboratories. It takes advantage of the high degree of control of chain length and architecture as well as graft density to design unique, highly grafted polymeric systems that can exhibit both compositional and conformational diversity of the backbone.

The group of Hammond evaluated the effect of polypeptide backbone rigidity on brush polypeptide gel network properties by swelling and mechanical testing studies. Results indicate that the equilibrium swelling and hydration properties of these synthetic polypeptide systems are quite unique. Both the L-propargyl glutamate and the D isomer can be used as monomers in generating these polymers, in which the all L polymer can form alpha helices and the D,L based
polymer forms random non-helical conformations. The polymers are then modified with oligoethylene oxide side chains \((\text{EO})_n\) varying in length from \(n = 3\) to 22. PPDLG gels exhibiting higher relative swell ratios due to the flexibility of the polymer backbone as compared to the rigid PPLG alpha-helix, and the PPLG gels also appear less sensitive to the size of oligoether brush that is clicked onto the backbone. As expected, polypeptides grafted with longer ethylene oxide brushes swelled more, at a factor of 10-14 depending on the polymer backbone (Figure 4). These results suggest the alpha helical secondary structure of the PPLG has some effect in restraining expansion of the hydrogel network and, to a certain extent, reduces the amount of swelling significantly as the fraction of PEO side chain becomes larger and the sidechains become bigger.

The mechanical properties of the series of gels have been investigated on the nano scale by atomic force microscopy (AFM) indentation and on the macro scale by rheological studies (Grodzinsky lab). Both methods show similar trends with respect to stiffness, where the PPLG hydrogels exhibit higher elastic modulus, presumably due to the rigid alpha-helix conformation of the polymer backbone. Additionally, gels with shorter PEG chains along the backbone (EO\(_3\)) are stiffer than those with longer PEG chains (EO\(_{22}\)); this observation is consistent in terms of swelling studies. The difference in elastic modulus values between the two methods cannot be compared directly due to the difference in contact area being measured. The AFM measurements are being performed on a nano scale while the rheology is an average of the hardness on the macro scale. The agreement of trends within the gels between both methods is consistent and affirms the premise that polypeptide geometry plays a role in determining mechanical properties. Furthermore, results of PPDLG-EO\(_{22}\) testing strongly suggest the dominance of poroelastic behavior likely due to the increased swelling capacity. It is possible the other gels can exhibit poroelastic behavior as well; however, a more sensitive technique would be required to further elucidate this behavior.

References

5. IRG-III: NANOIONICS AT THE INTERFACE: CHARGE, PHONON, AND SPIN TRANSPORT

Senior Investigators: Caroline A. Ross and Bilge Yildiz (co-leaders), Geoffrey S. Beach, Gang Chen, Harry L. Tuller, and Krystyn J. Van Vliet

Postdoctoral Associates: 3  Graduate Students: 9  Undergraduate Students: 0

Research Goals: This IRG aims to discover the coupling mechanisms between oxygen defects and the transport of phonons, spin and charge at the interfaces of metal oxides, with transformative implications for energy and information technologies. Although many structural and electronic factors are known to affect interface properties, it is believed that oxygen defects play a central role in these phenomena, but their role has thus far been under-explored. A tremendous opportunity exists to achieve further breakthroughs in understanding the role of confinement near oxide interfaces on ionic defect stability and mobility, described as nanoionics, impacting thermoelectrics, fuel cells, and memristive and magnetoelectronic devices. The IRG is organized into three interconnected and multidisciplinary thrusts.

Highlights of Research Accomplishments:

Thrust 1: Ion-Charge Coupling: Thrust 1 examines quantitatively how lattice strain, doping and electric field at interfaces impact the stability of oxygen defects and the kinetics of oxygen exchange and diffusion, which are directly relevant to memristor and fuel cell performance.

1.1 The defect chemistry of SrTiO$_3$ under finite electric field: Van Vliet and Yildiz have investigated SrTiO$_3$ as an archetypal material for functional metal oxides. Specifically, understanding and predicting the defect chemistry of SrTiO$_3$ with and without applied electric fields were deemed the first milestone in a focused modeling effort. Prior work has shown that while oxygen vacancies are preeminently the most studied defects in this oxide, several other defects such as antisites and cation vacancies could be equally important to electrochemical, magnetic and transport properties. To depict a comprehensive picture for the defect equilibria in this material without an electric field as a reference point, detailed density functional theory (DFT) calculations coupled with statistical thermodynamics have been started. The DFT energy model to represent SrTiO$_3$ was rigorously selected, and all needed convergence tests were completed. In a parallel activity, the effect of finite electric fields on the energetics and electronic structure of oxygen vacancies in SrTiO$_3$ were investigated using DFT equipped with Berry Phase formalism. Although prior work provides for a theoretical treatment of perfect crystal semiconductors under electric fields [1], various challenges arise in studying defective crystals. Within the past months, a critical assessment for these challenges was conducted and solutions to address these were formulated. In Figure 1a, a schematic of an oxygen vacancy in SrTiO$_3$ under zero field modeled...
using DFT is shown. Figures 1b and c show the induced polarization and the electric enthalpy of perfect crystal SrTiO$_3$ due to the applied electric field. The goal in the next stage is to calculate the electric enthalpy and polarization simultaneously for a defective SrTiO$_3$ for the first time.

1.2 Resistive switching in oxide thin films induced by scanning tunneling microscope tip: Resistance based random access memories (ReRAM) are considered as a promising alternative to current flash technology. The main advantages include simple architecture, high scalability, high density, high cycle performance, fast switching times and CMOS compatible technology. However, the durability of these devices is questioned given limited understanding of the switching mechanism—a highly localized phenomena occurring at atomic-scale dimensions. During this funding period, Tuller and Yildiz have pursued this understanding.

Scanning Tunneling Microscopy (STM) was used to investigate resistive switching behavior in TaO$_x$ and SrRuO$_3$ films as model systems representing conducting and insulating oxides. STM has a two-fold utility for characterizing ReRAM mechanisms. Firstly, high-resolution imaging enables investigation of switching phenomena locally. Secondly, information about the electronic structure and tunneling resistance (I-V curves) can be obtained, in relevance to the electrochemical processes in switching. Figures 2a-c show the localized switching of TaO$_x$ films by scanning the surface in the center of the image at a high voltage (+5V). The bright regions represent the formation of a low resistance state (LRS), as confirmed from Scanning Tunneling Spectroscopy (STS) (Figure 2d). By applying opposite polarity (i.e. -5V) on the LRS area, it is possible to return to the original high resistance state (HRS). Similar studies on SrRuO$_3$ (Figures 2e-h) revealed the LRS and HRS are obtained by applying -2.5 V and +2.5 V respectively, but only in presence of oxygen in the chamber. This indicates the switching mechanism in SrRuO$_3$ is different from TaO$_x$, and that oxygen defects play a vital role in SrRuO$_3$. The observed phenomena is highly repeatable and possible to switch areas as small as 2x2 nm$^2$.

Thrust 2: Ion-Phonon Coupling: This thrust exploits ion-phonon coupling to modulate oxygen vacancies under electric field to control phonon transport across interfaces, and to understand and quantify oxygen non-stoichiometry at oxide interfaces.
2.1 Thermal conductivity control by changing oxygen vacancy concentration in oxide thin films: A major focus of Beach, Yildiz, and Chen has been to manipulate ion-phonon coupling to control a material’s thermal conductivity and the interfacial thermal conductance between solid-solid interfaces. Previous studies under seed funding using an ultrafast pump-probe technique have shown that oxygen vacancy concentration in Pr$_{0.1}$Ce$_{0.9}$O$_2$-$\delta$ thin films can significantly affect their thermal conductivity, with a change of almost a factor of 2. First year results on SrCoO$_x$ ($x$: 2.5-3.0) dense thin films again confirm that oxygen defect concentration plays an important role in determining the thermal conductivity of SrCoO$_x$ (Figure 3). In the SrCoO$_x$ system, both the phase and the oxygen non-stoichiometry affect the thermal conductivity. SrCoO$_{2.5}$ is the brownmillerite (BM), and SrCoO$_{2.5<x<3}$ is the perovskite (P) phase. The transition between the BM and the P phases was induced by electrochemical pumping of oxygen into/out of the films, confirmed by in situ x-ray diffraction measurements. In addition, the experimentally observed thickness-dependent thermal conductivity in SrCO$_x$ films suggests ballistic phonon transport. Current work is also assessing the thermal conductivity of GdO$_x$ films (of great interest in Thrust (3)) as a function of electrochemically induced changes in $x$. Future work will focus on electrical gating to shuffle ions in/out of thin films and across interfaces to control thermal interface conductance and thermal conductivity.

Thrust 3: Ion-Spin Coupling Thrust 3 determines how oxygen defects at oxide-oxide and metal-oxide interfaces affect magnetic and spintronic behavior, enabling new spintronic devices.

3.1 On the effects of oxygen vacancies on magnetic properties in substituted perovskite oxides: Substituted perovskite oxides, such as transition metal (M = Fe, Co) substituted Sr(Ti,M)O$_3$, have exhibited room-temperature ferromagnetism when deposited under reducing conditions leading to a significant oxygen deficiency [2-4]. These studies and others determined that both strain and oxygen vacancies are capable of affecting the ferroic properties. The microstructure, magnetic properties, and ferroelectricity of oxygen-deficient Co-substituted SrTiO$_3$ (STCo) thin films grown on (100) SrTiO$_3$ were characterized (Ross) to better understand the effect of oxygen vacancy concentration and microstructure on the strain state and ferroic properties of this single-phase perovskite oxide film (Figure 4). Thin films of 50-200 nm were grown by pulsed laser deposition under vacuum, with 30%
Co on the Ti sites. The thinnest samples showed a cube-on-cube epitaxy in which the STCo had a (100) orientation with in-plane compression and a tetragonally distorted unit cell. Above a critical thickness the films formed a double epitaxial structure in which crystals of (110) orientation were embedded in the (100) matrix, both growing epitaxially to the substrate and having the same composition. This is the first report of double epitaxy in STCo, though it has been previously reported in Fe-substituted SrTiO$_3$ [5]. The microstructure and its effect on the magnetic and ferroelectric properties of the films were assessed. The thinner films had saturation magnetization up to 50 emu cm$^{-3}$ but this decreased for the thicker films. XPS excluded the presence of metallic Co and indicated the Co was a mixture of 2+ and 3+ valence states. Ferroelectric properties showed small remnant polarization. Density functional theory supported the enhancement of magnetic moment in a Co ion adjacent to an oxygen vacancy.

3.2 Strain coupling in spinel/perovskite nano-composites and its impact on magnetism and oxygen exchange kinetics: Spinel/perovskite nano-composites differ from their single phase constituents in their magnetism [6], electronic conductivity [7], ionic conductivity [8], and catalytic activity [9,10]. The model systems (Yildiz and Ross), CoFe$_2$O$_4$/La$_{0.8}$Sr$_{0.2}$CoO$_3$ (CFO/LSC) and CoFe$_2$O$_4$/Ba$_{0.5}$Sr$_{0.5}$Co$_{0.8}$Fe$_{0.2}$O$_3$ (CFO/BSCF), were used to explore the effects of the hetero-interfaces on magnetism and oxygen reduction kinetics. While CFO is a well-known ferrimagnetic material, LSC and BSCF are two of the most widely studied mixed electronic and ionic conductors that have fast oxygen exchange kinetics important for fuel cells. CFO/LSC and CFO/BSCF nano-composites with 140 nm thickness were deposited by pulsed laser deposition on (001) SrTiO$_3$ (STO) substrates by alternating the ablation of CFO and LSC (or BSCF) targets. X-ray diffraction (Figure 5a)) and Transmission Electron Microscopy (TEM) measurements (Figures 5b-c) showed that CFO/LSC and CFO/BSCF composite structures were crystalline with coherent interfaces, with the film consisting of intermixed crystals of the two phases. The magnetization hysteresis loops of CFO/LSC and CFO/BSCF differed from single phase CFO, (Figures 5e-f) due to the different strain state and crystal geometry. CFO is under compressive strain along the out of plane direction imposed by LSC and BSCF. Further studies to test the oxygen exchange kinetics of the composite films are ongoing.

3.3 Correlation between magnetic, electrical, and optical switching Co/GdO$_x$/gate structures: The oxygen coordination at a ferromagnetic-metal/metal-oxide interface has a strong influence on magnetic properties, and a gate voltage applied across the GdO$_x$ layer in Co/GdO$_x$/gate structures can displace O$^{2-}$ ions near the Co/GdO$_x$ interface and thereby modify interfacial magnetic properties [11]. The initial focus of this IRG effort has been a systematic characterization of the effects of voltage cycling in Co/GdO$_x$/gate structures (Beach and Tuller). Figure 6a shows an I-V curve for a 200 mm diameter Au gate electrode grown on a Si/Ta(4nm)/Pt(3nm)/Co(0.9nm)/GdOx(4nm)/gate film. The Co layer is fully oxidized during film growth, and is therefore nonmagnetic (Figure 6b). As gate voltage $V_g$ is increased, the device
switches to a low-resistance state (Figure 6a) at $V_g=+5V$, and back to a high resistance state at $V_g=+8V$. This second resistive switching event is accompanied by abrupt changes in magnetic and optical properties (Figure 6c). The Co changes abruptly from oxidized to metallic, and the magnetic anisotropy changes from in-plane to out-of-plane and back to in-plane with interface oxidation. Following the initial voltage cycle, the voltage response changes markedly: the Co layer can be switched reversibly between out-of-plane and in-plane by cycling $V_g$ between 0V and +3V, and these changes are accompanied by reversible changes in optical reflectivity. The next steps will be to correlate these properties (electrical, optical, magnetic) with oxygen defect concentrations and distributions, and to extend these studies to perovskite oxides.

![Figure 6](image)

**Figure 6**: (a) I-V curve for a Pt/Co/GdOx/gate structure. Inset: low-voltage I-V curves. (b) Out-of-plane magnetization hysteresis loops after V cycling. (c) Optical micrographs of gate electrode after first applying $V_g=10$ V, and then cycling between $V_g=0$ V and $V_g=+4$V, showing color change in electrode by voltage application.

References

Chemically Modified Carbon Cathodes for High Capacity Li-O₂ Batteries
PI: Yogesh Surendranath, (Dept. of Chemistry – recipient of a recent NSF Career Award)
Graduate Students: 

Research Summary: Li-O₂ batteries are poised to transform the consumer electronic and electric vehicle markets because they possess a theoretical energy density of 3,213 Wh/kg, threefold larger than the current state of the art. This dramatic boost in energy density is provided by the carbon-based Li-O₂ cathode, at which O₂ is reduced to Li₂O₂ upon cell discharge. However, the insoluble Li₂O₂ precipitates indiscriminately on the surface of the carbon cathode, inhibiting subsequent reduction of O₂ (Figure 1, left), leading to diminished capacity, poor rate capability, and poor round-trip efficiency. These challenges could be overcome if the surfaces of carbon cathodes can be modified to discourage the indiscriminate nucleation and growth of Li₂O₂ crystallites. The Surendranath group has embarked on this endeavor by first developing a passivating layer on carbon-based electrodes that can be tuned with precision.

Importantly, the targeted passivating layer must inhibit access of Li⁺ to surface nucleation sites (Figure 1), but must be thin enough to permit facile charge transfer to O₂ to form Li₂O₂ – too thick of a passivating layer would serve to inhibit both charge transfer and nucleation. To balance these two competing requirements, Surendranath has developed a novel passivation method that relies on oxidation of common aryl hydrazines to generate an aryl radical that is then captured by the carbon surface. Deposition occurs in seconds and can be tuned by controlling the applied potential and time duration. Cyclic voltammetry (Figure 3) of an aqueous solution of pentafluorophenylhydrazine (R = F₅) exhibits an large wave at 1.0 V vs. RHE arising from oxidation of the hydrazine, and subsequent scanning reveals a pronounced inhibition of the hydrogen evolution wave at −1 V. This indicates that deposition of the aryl layer is effective at inhibiting binding of protons to the surface, suggesting that this passivation will be particularly effective at blocking Li₂O₂ nucleation. Surface deposition of C₆F₅ groups was confirmed by X-ray photoelectron spectroscopy (XPS), revealing monotonic growth of surface fluorine content with additional deposition cycles (Figure 3, inset). While the passivating layer effectively inhibits H⁺ binding and H₂ evolution, rapid outer-sphere charge transfer to soluble redox hosts is preserved. Together these exciting initial results indicate that this passivation method is ideally suited to preparing advanced Li-O₂ battery cathodes. Future studies will investigate the Li₂O₂ nucleation and growth on these modified surfaces.
5. Seed 2

Interface Engineering of Silicon-Oxide Core-Shell Nanorods for High-Efficiency Water Splitting Photocatalysts
PI: Alexie M. Kolpak, (Dept. of MechE)
Postdoctoral Associates: 1 Graduate Students: 1

Research Summary: Photocatalytic water splitting using solar energy is a promising process for renewable hydrogen production, but a better conversion efficiency is needed to make it economically viable. This requires new materials with optimized band alignment, visible light absorption, exciton separation, electron and hole carrier mobility, hydrogen and oxygen evolution activity, and photo-corrosion resistance. In this work, ab initio computations are used to investigate the properties of Si-TiO$_2$ core-shell nanorods as candidates for optimizing these key metrics. Figure 1 illustrates the conceptual approach, which aims to take advantage of (a) nanoscale geometry, which orthogonalizes light absorption and carrier separation; (b) the known resistance of TiO$_2$ to photo-corrosion in water; and (c) the potential ability to modify synthesis conditions to engineer the interfacial stoichiometry in this system to obtain a 2D electron or hole gas at the interface.

In the first six months of the project, the thermodynamic stability and electronic properties of Si-TiO$_2$ interfaces with varying stoichiometry were investigated using density functional theory (DFT) along with a Hubbard U correction to mitigate the well-known band gap problem and obtain the experimental bulk TiO$_2$ band gap. Figure 2 shows the free energy of the different interface phases as a function of oxygen chemical potential $\mu_O$, and Figure 3 shows the atom-projected density of state (DOS) for these phases, which demonstrate metallic behavior at the interface for the stable phases at low $\mu_O$. The results suggest that low $\mu_O$ growth conditions lead to oxygen-poor films, which leads to a 2D conducting electron gas at the interface. The origin of this phenomenon is an interfacial dipole that traps oxygen vacancies at the interface. Over the next six months, the effect of the stable interfaces on catalytic activity will be evaluated. This will be done by computing the free energies of the four electron-proton transfer steps of the oxygen evolution reaction on the TiO$_2$ surface for films with each of the stable Si-TiO$_2$ interface phases. The electronic conductivity of the 2D conducting electron gas will also be determined.
Single Crystal Study of Electronic Topology and Correlation
PI: Joe Checkelsky, (Physics)
Postdoctoral Associates: 1
Graduate Students: 1
Undergraduate Students: 1

Research Summary: A relatively unexplored parameter in topological systems is electronic correlation. Motivated by the metal-insulator transition observed in the pyrochlore iridates $R_2\text{Ir}_2\text{O}_7$ ($R$ is a rare earth, see Figure 1a) it has been suggested that a combination of weak to moderate correlation effects and large spin-orbit interaction may exist that could give rise to new topologically non-trivial electronic states. In particular, it is expected that this compound’s principle bulk excitations may be described by a 3-dimensional analog of graphene known as a Weyl semimetal with helical excitations in all 3 dimensions (Figure 1b, only one chirality shown here) with a several exotic and potentially useful properties. Checkelsky proposes to extend a flux technique reported for $R=$Eu and Pr across this series to develop high quality single crystals and perform incisive studies of the magnetic transition and transport properties of the electronic ground state. This study would open the door for other optical and scattering experiments; other potential systems for parallel study include Os oxides and spinel candidate compounds.

Since the beginning of this SEED project, the Checkelsky group has pursued the synthesis of single crystals of $R_2\text{Ir}_2\text{O}_7$ and spinel compounds including CdCr$_2$Se$_4$. Flux growth has been employed for the former and vapor transport/melt growth for the latter. Though originally anticipated to be more challenging, in fact the most successful synthesis has been for spinel CdCr$_2$Se$_4$ using melt growth, where single crystals of the target phase up to 1 mm in size have been achieved (Figure 2). The group is now studying the magnetic properties of this compound as well as its electrical transport properties. As grown, it is a lightly doped semiconductor with n-type carriers. Combining this system with heavier dopants is expected to drive a bulk Fermi surface transition and generate the Weyl points shown in Figure 1(b) above. A preliminary result is that annealing the crystals with and without Se powder allows for tuning of the carrier density presumably through defect chemistry. Study of the magnetic properties of these crystals indicates a ferromagnetic transition near 120 K- this symmetry breaking is needed to realize the Weyl phase. The dependence of this transition on chemical doping is now being studied. Single crystal synthesis of $R_2\text{Ir}_2\text{O}_7$ is ongoing.

Figure 1. (a) Pyrochlore Iridate structure $R_2\text{Ir}_2\text{O}_7$ ($R$ = rare earth element). (b) Electronic structure characterized by Weyl point

Figure 2. Single crystals of CdCr$_2$Se$_4$ that exhibit ferromagnetism.
The following seed was approved at the start of the grant, but was only launched in July of 2015.

**Direct Deposition of Catalysts on Porous Metallic Foams for Efficient CO\textsubscript{2} Electroreduction**

**PI:** Fikile R. Brushett, (Dept. of ChemE)

**Research Summary:** The development of energy efficient carbon dioxide (CO\textsubscript{2}) electroreduction processes would simultaneously curb anthropogenic CO\textsubscript{2} emissions and provide sustainable pathways for fuel generation. While significant efforts have focused on heterogeneous CO\textsubscript{2} electroreduction to products such as carbon monoxide, formic acid, and methanol; no process has been able to demonstrate both high energetic efficiencies ($\geq 60\text{-}70\%$) and high current densities ($\geq 150$ mA/cm\textsuperscript{2}). A key challenge is translating our investment in performance nanomaterials to meso- and microarchitectures within electrochemical cells under realistic operating conditions. Here we propose to develop microporous metal foam electrodes with nanostructured electrocatalysts directly deposited onto the foam surface for high-performance CO\textsubscript{2} conversion (Figure 1). Metal foams hold two key advantages: 1) their porous nature facilitates extended tunable electrochemical interfaces without sacrificing transport of reactants and ions; and 2) they can act as a conductive substrate for the direct deposition of highly-active surface alloys eliminating the need for conductive additives and binders (which may degrade or promote side reactions). We will focus on CO-selective catalysts (e.g., Ag, Au) as this represents the simplest CO\textsubscript{2} conversion reaction and has been demonstrated at moderate efficiencies (albeit at low currents). Direct deposition enables ground-up construction of nanostructures using bath conditions (e.g., composition), delivery mechanism (e.g., diffusive, convective), and applied potential (for electrodeposition) as tools to control structure, phase, and surface characteristics. We will systematically investigate the structure-activity-stability relationships of the deposited catalysts and electrodes using electroanalytical and physical characterization techniques. Of particular interest will be catalysts deposited under transport limiting conditions (desirable for high-throughput manufacturing) and catalyst-substrate interactions (determines durability). The success of this project would enable efficient CO production at the large-scale which, when coupled with hydrogen generation from renewables enables the carbon-neutral synthesis gas production needed to generate liquid fuels for heavy duty transportation applications.

**Figure 1:** A schematic of the foam electrode with a directly deposited catalyst layer for CO\textsubscript{2} reduction at multiple length scales. Additional reactants & products not shown for clarity.
CMSE’s portfolio of education programs is designed to enhance the knowledge and skills of K-12 students and teachers and to promote a more scientifically literate citizenry. The center also provides programs to train undergraduates, graduate students, and postdoctoral associates to become future leaders in science and engineering research and education. The MRSEC’s core education programs are described below. Each program is assessed on an annual basis to assure that it meets its goals and objectives. Assessment tools include entrance and exit surveys, focus groups, and tracking the careers of REU participants.

Research Experience for Teachers (RET): Each summer the MRSEC provides local science teachers with research experience in materials science and engineering. Objectives of the program are to familiarize them with current materials research, increase their science and engineering content knowledge, facilitate the development of new classroom material, and cultivate long-term relationships between CMSE and teachers. Each participant spends seven weeks working closely with graduate students and postdocs as a member of a faculty-led research group. In addition to the research, the teachers are introduced to the equipment in the MRSEC’s SEFs and attend weekly discussion meetings to share their research and lesson plans with each other and explore connections to their classroom teaching. They are also introduced to the extensive assortment of education activities, workshops, and programs for K-12 teachers and students offered by MIT departments and centers throughout the year. At the end of the summer, the teachers present their research in a joint RET/REU poster session attended by the entire materials community at MIT. Participants are encouraged to return for a second summer to continue their research and/or develop classroom units or lab projects based on their research experience.

Teachers are recruited from local school systems and through former participants in the MRSEC’s MIT’s K-12 educator programs. Participants are selected on the basis of their teaching experience, research interests, and statements of intended use of the RET to enhance their classroom teaching. CMSE dedicates approximately half of the RET positions to teachers from local schools that have highly diverse student enrollment. Each participant is awarded a stipend and a small budget for classroom supplies. The 2015 cohort included three K-12 teachers and two faculty members from local community colleges. Three of the participants taught in schools with enrollments of more than 50% underrepresented minority students.

**RET Participants, 2015**

<table>
<thead>
<tr>
<th>Name</th>
<th>School/Subject(s) Taught</th>
<th>Research Project or Lesson Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amini, Ali</td>
<td>Roxbury Community College</td>
<td>Design of inductively driven alternating field magnetic coils</td>
</tr>
<tr>
<td></td>
<td>Roxbury (Boston), MA (Mathematics, Physics)</td>
<td></td>
</tr>
<tr>
<td>Ciocan, Eugenia</td>
<td>Bunker Hill Community College</td>
<td>Dimentional and functional characterization of magnetic vortex nanoparticles for biological applications</td>
</tr>
<tr>
<td></td>
<td>Charlestown, MA (Physics)</td>
<td></td>
</tr>
<tr>
<td>Müller, Sean</td>
<td>Merrimack High School</td>
<td>Practical magic: Teaching students mechanical and electrical engineering using modern fabrication processes</td>
</tr>
<tr>
<td></td>
<td>Merrimack, NH (Chemistry)</td>
<td></td>
</tr>
<tr>
<td>Oluwanifemi, Mabayoje</td>
<td>East Boston High School</td>
<td>Additive printing of microreactors for continuous flow synthesis</td>
</tr>
<tr>
<td></td>
<td>Boston, MA (Chemistry, Physics)</td>
<td></td>
</tr>
<tr>
<td>Nigdelioglu, Ramazan</td>
<td>Cambridge Rindge and Latin High School</td>
<td>Chemical vapor deposition (CVD) synthesis of molybdenum disulfide</td>
</tr>
<tr>
<td></td>
<td>Cambridge, MA (Physics)</td>
<td></td>
</tr>
</tbody>
</table>

An important feature of CMSE’s RET program is the ongoing relationships established between the MRSEC and local science teachers. Over the years, these continued collaborations have
enabled class visits to MIT, K-12 school presentations by MRSEC researchers, and student involvement in research. For instance, in April, 2015 RET participant Prof. Kasili brought a total of 25 students from his two community college biology classes to visit the CMSE X-ray SEF. In addition, one of the 2015 participants, Sean Müller, has worked with CMSE on many projects over the years developing lab projects that are used both in his high school classroom as well as in one of MIT’s freshman seminars.

Science Teacher Enrichment Program (STEP): The 2015 STEP, subtitled “Dustbusting by Design” was a four-day workshop correlated to the Massachusetts state science learning standards and focused on increasing middle and high school teachers’ content knowledge of and experience in engineering design. Participants spent three and a half days learning about the design challenges associated with the motor in a hand-held vacuum, then immersing themselves in the engineering design process as they constructed motors of their own design. The final half-day consisted of seminar on teaching the design process in K-12 classrooms. The lab portion of the program is simultaneously taught to 40 high school girls in the Women’s Technology Program (see below). Participants in STEP received a small stipend and professional development hours. They were recruited from local school districts, from former applicants to CMSE’s RET program, and through other MIT-based programs for educators. Two high school teachers participated in the 2015 STEP. Entrance and exit surveys were used to determine how well participants felt this workshop met their needs. Both teachers responded that the program more than met their expectations and provided them with material they intend to use with their students. One replied, “This was a great experience. The lab staff were magnificent, the professor inspiring, the opportunity to observe the learning process with high school students very fruitful for a practicing teacher. . . .” I was looking for a novel engineering professional development [program] and I got it and then some!”

Women’s Technology Program in EECS (WTP-EECS): CMSE collaborates with EECS on a four-week, residential program for high school girls by presenting a hands-on engineering design class. The goal of WTP-EECS is to address the gender imbalance in the field of engineering by sparking the girls’ interest and confidence in pursuing engineering careers. (This motor-building class was taught simultaneously to the STEP teachers and WTP students.) It began with a day of lectures by Prof. Leeb on the physics of dc motors and the engineering design process. During the following three days, the students worked in pairs to design and construct their own motors. Participants were selected based on their academic record, teacher references, personal statements, and PSAT, SAT or ACT scores. EECS surveys WTP participants after the conclusion of the program each year and tracks their academic careers beyond high school. 100% of eligible former WTP-EECS participants have enrolled in college. (See Diversity section for details on the 2015 program.)

Science and Engineering Program for Middle School Students: The long-standing summer middle school program seeks to introduce local adolescents to materials science and engineering, excite them about science and engineering, and give them an opportunity to experience a college environment firsthand. Students from the local Putnam Avenue Upper School were selected by their science teacher, who attended the program with the students. 57% of the students attending the school are members of underrepresented minority groups. Thirteen rising seventh- and eighth-grade students attended the 2015 program, seven of whom were girls. Because the students are on campus from 8:00 A.M. to 3:00 P.M. each day, meals are provided by CMSE. The Center also provides bus transportation between the schools and MIT. While on campus, the students participated in hands-on activities presented by faculty, staff, graduate students, and undergraduates. The 2015 program included classes on UV light, DC motors, electric circuitry, polymers, glassblowing, metal casting, sensors, and solar cells. In discussions at the end of each day the students described the material presented and explained what they saw. An indication that the program met the goal of demonstrating that science and engineering are fun is that all of the students who completed exit surveys responded that they
would recommend the program to their friends. One commented, “The program helped me learn so much about new things!” When asked if they had suggestions to improve the program, a student responded, “No it’s really good as it is and anyone who didn’t like this program is crazy.”

Other Programs for K-12 Students and Teachers, and the Public: MRSEC faculty and students contributed content to programs on campus and at local public events. On March 28th, four graduate students presented energy-related demonstrations at “Science, Engineering, and Technology in the City,” a full-day program of lectures, demonstrations, hands-on lab projects, and panel discussions attended by approximately 200 local high school girls. This program is organized by the Boston Area Girls STEM Collaborative, of which the MRSEC is a member. Prof. Leeb leads several outreach efforts each year. In April he presented a table-top activity at the Winnbrook Elementary School’s (Belmont, MA) Science Night for parents and students. About 200 students and parents attended the 2015 event. In June 2015, for the seventh year, he taught engineering experiments to 40 students in the Research Science Institute (RSI). RSI is a well-established national six-week research program for high-achieving high school students sponsored by the Center for Educational Excellence each year and held on the MIT campus. MIT also hosts a group of science teachers for a week each June for the Science and Engineering Program for Teachers. This professional development program has been in place for 27 years and features faculty lectures on new frontiers in science and engineering research, as well as hands-on workshops. During the 2015 program, Professor Ross presented a lecture, “Magnetic Materials and Applications,” to the 30 participants and Professor Belcher spoke on “Giving New Life to Materials for Energy, the Environment and Medicine.” In addition, Felice Frankel, a research scientist at CMSE, presented “Picturing to Learn: How Images Can Teach Science and Engineering,” to the group.

Community College REU Program (CCP): The MIT MRSEC partners with local Roxbury (RCC) and Bunker Hill Community Colleges (BHCC) to provide their students with research opportunities and encourage them to pursue careers in science, engineering, and technology. Participants for the CCP are selected by science faculty at their home institutions. Selection criteria include the students’ academic background, statements of interest, and faculty references. A total of six students participated in 2015, three of whom were women and one of whom was a minority student. CCP students spent nine weeks on campus conducting research in faculty-led groups. They joined the other REU students for weekly meetings and seminars. These meetings featured research discussions and speakers on intellectual property, graduate school admission, preparing science and engineering images for presentations, and hot topics in materials science and engineering. CCP participants presented their research in the RET/REU poster session.

**CCP REU Participants, 2015**

<table>
<thead>
<tr>
<th>Name</th>
<th>Home Institution/Major</th>
<th>Research Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Howe, Christina</td>
<td>Bunker Hill Community College Biology</td>
<td>Study and improvement of alternating magnetic field setups</td>
</tr>
<tr>
<td>Napoleon, MarcArthur</td>
<td>Roxbury Community College Biotechnology</td>
<td>Effect of plastic strain on corrosion of X65 carbon steel</td>
</tr>
<tr>
<td>Ouarrak, Mohamed</td>
<td>Roxbury Community College Engineering</td>
<td>Investigation of the effects of surfactant concentration on the boiling curve of water</td>
</tr>
<tr>
<td>Son, Soo</td>
<td>Bunker Hill Community College Engineering</td>
<td>Artificial tribotactic microscopic waters</td>
</tr>
<tr>
<td>Topaz, Gemma</td>
<td>Roxbury Community College Biological Science</td>
<td>Optogenetic Schwann cell stimulation for nerve regeneration</td>
</tr>
<tr>
<td>Uthayakumar, Latha</td>
<td>Bunker Hill Community College Biomedical Engineering</td>
<td>Artificially engineered protein hydrogels with modulating sequences for controlling selective molecular transport</td>
</tr>
</tbody>
</table>
Summer Research Internship Program (REU): In collaboration with the Materials Processing Center (MPC), CMSE operates an REU program. Participants, who are rising junior and senior undergraduates, were selected on the basis of their academic record, statements of interest, and faculty recommendations. The application review committee for 2015 consisted of the CMSE director, assistant director, education officer, and three MPC staff. The twelve interns listed below were selected from approximately 180 applicants. They included six women and five minority students. Because the CMSE/MPC program is well established as a quality internship program on campus, other organizational units seek to fold their summer undergraduate researchers into the program. Last summer, the stipends of two students in the REU program (marked with asterisks) were paid by an Energy Frontier Research Center funded by the US Department of Energy, Office of Basic Energy Sciences, under Award Number DE-SC0001299. These two students were selected from the pool of applicants to the REU program and participated fully in the program.

CMSE/MPC Summer Interns, 2015

<table>
<thead>
<tr>
<th>Name</th>
<th>Home Institution/Major</th>
<th>Research Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrett, Lena</td>
<td>Lehigh University Chem. E., Business Inf. Systems</td>
<td>A novel catalytic process for the one-pot production of neopentyl glycol from Isobutyraldehyde and formalin</td>
</tr>
<tr>
<td>Caraballo Santa, Mariely</td>
<td>University of Turabo Mechanical Eng.</td>
<td>Degradation of submarine propulsion shafts: development of prototypic test sample</td>
</tr>
<tr>
<td>Fiebig, Olivia</td>
<td>Rowan Univ. Chemistry, Physics</td>
<td>Amino acid substitution as a method to change macroscopic behavior in ELP protein hydrogels</td>
</tr>
<tr>
<td>Gibbs, Stephen</td>
<td>Univ. of Florida Chemical Eng.</td>
<td>Enhancing voltage output of thermopower waves through magnetic flux compression</td>
</tr>
<tr>
<td>Greco, Katharine</td>
<td>Univ. of Massachusetts, Amherst Chemical Eng.</td>
<td>X-ray diffraction for the characterization and modeling of hybrid semiconductor nanocrystals</td>
</tr>
<tr>
<td>Lin, Zhenni</td>
<td>Rutgers Univ. Materials Science and Eng.</td>
<td>Synthesis and characterization of pH-sensitive solid magnetic resonance imaging contrast agents</td>
</tr>
<tr>
<td>Machielse, Bartholomeus</td>
<td>Univ. of Pennsylvania Physics</td>
<td>Structures and materials for infrared photonics</td>
</tr>
<tr>
<td>Rosado Vega, Jahzeel</td>
<td>University of Turabo Mechanical Eng.</td>
<td>Kinetic energy propagation and wave speed in silk materials</td>
</tr>
<tr>
<td>Savagian, Lisa</td>
<td>Hope College Chemistry</td>
<td>Photothermal layer-by-layer Films for on-demand drug delivery</td>
</tr>
<tr>
<td>Sengupta, Jonah</td>
<td>Univ. of Maryland Electrical Eng.</td>
<td>Piezo-solvo annealing: A new frontier in BCP alignment</td>
</tr>
<tr>
<td>Zhao, Nathan</td>
<td>Columbia Univ. Physics, Mathematics</td>
<td>Modeling coarsening in immiscible multilayers</td>
</tr>
</tbody>
</table>

The nine-week summer internship program began with a three-day symposium during which faculty presented their research, describing the projects available for the interns. At the end of the three days, the interns selected their projects for the summer. Throughout the summer, the
interns, along with the CCP REU students, participated in weekly mentoring meetings and seminars. They also presented their research at the RET/REU poster event in August. The students will complete surveys at the end of the program.

**Undergraduate Research Opportunities Program (UROP):** The Center provides opportunities for MIT undergraduates to participate in MRSEC research through MIT’s UROP. Participants in this program work on MRSEC research on a part-time basis during the academic year and full-time during the summer. The MRSEC supports two students each term, some of whom continue their research for multiple terms. Additional undergraduates work on MRSEC research for academic credit or are supported with MIT funds. During the reporting period, CMSE funded three students, of whom one was female and one was a minority student. Faculty report that an additional nine UROP students (five female, two minority) worked on MRSEC research.

**CMSE-funded UROP Students, February-August 2015**

<table>
<thead>
<tr>
<th>Student</th>
<th>Department</th>
<th>Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alvarez, Brian</td>
<td>EECS</td>
<td>Design of circuitry class materials and labs</td>
</tr>
<tr>
<td>Rivera, Nicholas</td>
<td>Physics</td>
<td>Separable Bound States in the Continuum</td>
</tr>
<tr>
<td>Sayre, Larkin</td>
<td>Mechanical Eng.</td>
<td>Designing, machining, and assembling kits for use in freshman and high school electrical engineering classes</td>
</tr>
</tbody>
</table>

**Graduate and Undergraduate Education:** CMSE regularly supports graduate students working in IRG, initiative, and seed research through research assistantships. Students supported with fellowships also participate in MRSEC research. CMSE’s SEFs contribute significantly to the education of both graduate and undergraduate students by training them to operate the state-of-the-art equipment. In addition, the SEFs offered four mini-courses during MIT’s Independent Activities Period in January 2015.
7. POST-DOC MENTORING PLAN

Same as in original proposal.
7. DATA MANAGEMENT PLAN

Same as in original proposal.
8. CENTER DIVERSITY

CMSE’s diversity plan consists of three integrated strategies designed to increase participation by women and traditionally underrepresented groups in its research and education programs: (1) to increase participant diversity in the MRSEC’s existing programs, (2) to develop and refine dedicated programs that target underrepresented groups, and (3) to collaborate with other offices and departments at MIT and beyond to enhance diversity on campus and in science and engineering fields.

Enhancing diversity within existing programs: To increase minority participation in its Summer Internship Program (REU), CMSE directly advertises the program to minority-serving institutions. In the fall of 2014, approximately 400 letters with recruitment flyers were sent to principal investigators at NSF-funded Centers for Research Excellence in Science and Technology (CRESTs), Historically Black College and University Research Infrastructure for Science and Engineering awardees (HBCU-RISE), and Louis Stokes Alliances for Minority Participation (LSAMPs). CMSE also recruited via the Institute for Broadening Participation’s online directory of REU programs. The number of applications from women and minority students has gradually increased since the beginning of the grant. Applications received for the 2015 program showed an increase in minority applicants (20%) compared to last year (16%). Women consistently comprise approximately one-third of the applicants. To further increase diversity in the REU program, the Center runs collaborative programs with two local community colleges and the Universidad Metropolitana (UMET) in Puerto Rico, all of which serve underrepresented minority students (see “Targeted programs” section below).

Recognizing the importance of 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 approximately 50% participation by teachers from schools with significant enrollments (>50%) of underrepresented students. Three of the five participants in the 2015 RET program taught at institutions that meet this requirement. In addition, CMSE directly engages local middle school students through its Science and Engineering Program for Middle School Students. Students who participated in the 2015 program were drawn from the Putnam Avenue Upper School, where 57% of the registered students are from underrepresented minority groups.

Targeted programs: CMSE seeks to address the shortage of young women pursuing engineering careers through its collaboration with MIT’s Women’s Technology Program (WTP). The MRSEC contributes a four-day class to this summer program administered by EECS. The goal of the four-week WTP-EECS is to increase girls’ interest in engineering and to enhance their confidence in their ability to succeed in engineering careers. It targets high school girls with strong math and science backgrounds who have not decided on college majors. Forty high school women participate in this residential program each summer. While on campus, they attend lectures and classes taught by female faculty and graduate students, and are mentored by female MIT undergraduate tutors. The motor-building class given by CMSE provides most of them with their first experience of hands-on engineering design. The students continue to report that their experience in WTP-EECS increased their confidence in their ability to succeed in science and engineering. To date, 546 young women have participated in this program. Of the 390 who have reported college majors at this point, 331 chose to major in science, engineering or math.

CMSE continues its partnership with the Universidad Metropolitana (UMET) in San Juan, Puerto Rico, the objective of which is to enhance the research skills and experience of students at Puerto Rican universities and high schools. An additional goal is to recruit and retain Puerto Rican science, technology, and engineering graduates. Dr. Juan Arratia, Executive Director of
the Student Research Development Center at UMET, refers two students to the CMSE/MPC Summer Internship Program (REU) each year. Since the inception of the program, 17 students have participated in the program and an additional two students spent two weeks at CMSE working with MRSEC graduate students to use research instruments in the SEFs. In addition to their research at MIT, undergraduates who participate in the REU program contribute to the UMET's outreach program to high school students in the San Juan area. Of the 19 students who have been through the program, four are still completing their undergraduate studies. Another five have proceeded to graduate school, one of whom has completed her PhD. Six others completed their bachelor degrees and are employed: three as engineers, one as a financial consultant, one in manufacturing, and one as a systems analyst. The career status of the remaining students is unknown. MRSEC director, Rubner has visited UMET annually to present lectures, meet with students and faculty, and discuss continuing collaborations. Future visits to UMET by MRSEC faculty and graduate students are planned. This partnership has been enhanced through the use of MRFN funds to bring UMET faculty and students to MIT to use SEF equipment for their research. In June 2015, a graduate student who visited in 2014 with Professor Primera returned with two undergraduates to spend a week using the Electron Microscopy, Materials Analysis, and X-ray SEFs for additional sample characterization. The undergraduate students were trained to use the instruments. Professor Cotto and her graduate student from the Universidad Turabo are planning to return in September to continue work on their research using the SEFs.

CMSE’s Community College Program (CCP) is a third targeted program designed to reach an underserved undergraduate population. Students from two local community colleges that enroll significant numbers of minority students (50% at one and 64% at the other) participate in the CCP each summer as REU students. Over the eleven years that the program has been in place, 57% of the 54 participants have been minority students and 46% 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 the CCP, they learn research and technical skills that increase their confidence and prepare them to pursue bachelor degrees and science and engineering careers. The students report that, in addition to enhancing their research skills, their experience at MIT broadened their knowledge of possible science and engineering careers and provided a realistic picture of graduate work. Since the beginning of the CCP, 32 (59%) of the participants have transferred to, or received their A.S. degree and enrolled in, four-year colleges. Of those, 4 have enrolled in graduate programs. Three of them are currently pursuing graduate degrees in science and engineering, and another is earning an MBA. An additional student went on to medical school. Six CCP participants proceeded directly from community college to employment. Nine students continue at the community colleges, and the status of 7 other participants is unknown. For the past three summers, the MRSEC has broadened the impact of its community college partnerships by collaborating with Prof. Anikeeva to engage BHCC and RCC faculty and students in her lab’s research. With CMSE support and her NSF CAREER grant funds, she hosts two students and a professor from each community college each summer. The students participate in the Center's REU program and the faculty are folded into the RET program. In addition, Prof. Anikeeva presents lectures and seminars at the community colleges.

Collaborations with other MIT units: CMSE works with other departments and centers at MIT to achieve mutual diversity objectives. The WTP is an example of such a partnership. As a member of the K12@MIT community on campus, the MRSEC education officer is informed about the wide range of education programs offered so that the Center can partner with other units and student groups when appropriate. MIT is engaged in an institution-wide effort to achieve greater diversity at all levels on campus. The Institute Community and Equity Office
presents a speaker series, makes modest grants to support projects that promote multicultural understanding, and sponsors an annual Institute Diversity Summit for the entire community. This multi-day program consists of speakers, panel presentations, films, and workshops. The MRSEC director contributed to the initial diversity summit several years ago. The assistant director and education officer participate in these events annually.

Center participants are drawn from the available pool at MIT. While CMSE does not directly hire faculty or postdoctoral associates, it does help academic departments attract researchers by presenting them with opportunities for seed funding, special awards to cover SEF usage, interdisciplinary collaboration and access to state-of-the-art research instrumentation. In addition, to increase diversity at the faculty level, the MRSEC participates in Future Faculty Workshops, the objective of which is to provide intensive mentorship to underrepresented senior graduate students and postdocs who aspire to academic careers in the fields of polymer, materials, and supramolecular science. Professional development topics such as career planning, job interviewing and negotiating skills, and understanding unwritten rules in career paths are typically addressed.

The director works with department heads, deans, and administrators to attract and retain members of underrepresented groups at all levels. Progress in diversifying the undergraduate population has been made in recent decades. As of fall 2014, 46% of MIT undergraduates were women and 24% were members of underrepresented groups. More progress needs to be made at the graduate student and postdoc levels. 32% of the graduate students at MIT are women and 8% are underrepresented minority students. Strategies to increase the diversity of CMSE’s graduate students include attracting more women and minorities to programs such as the summer internship, community college, and UMET programs to increase the pipeline of qualified candidates for admission to MIT. CMSE’s diversity goals include 50% participation by women and 50% by minority students in the combined undergraduate programs (Summer Internship, UMET and Community College Programs). CMSE has met or surpassed the goal for women participants in recent years. Although minority participation had steadily increased to 40% in 2014, the numbers fell for the summer of 2015.

**MRSEC Program Participants, November 2014-August 2015**

<table>
<thead>
<tr>
<th>Program</th>
<th>Total Participants</th>
<th>Female</th>
<th>Minority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle School Program</td>
<td>13</td>
<td>7 (54%)</td>
<td>4 (31%)</td>
</tr>
<tr>
<td>Women’s Technology Program</td>
<td>40</td>
<td>40 (100%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Research Experience for Teachers</td>
<td>5</td>
<td>2 (40%)</td>
<td>1 (20%)</td>
</tr>
<tr>
<td>Science Teacher Enrichment Program</td>
<td>2</td>
<td>1 (50%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Summer Internship Program (REU)*</td>
<td>12</td>
<td>6 (50%)</td>
<td>2 (17%)</td>
</tr>
<tr>
<td>Community College Program (REU)</td>
<td>6</td>
<td>3 (50%)</td>
<td>1 (17%)</td>
</tr>
<tr>
<td>Undergraduate Research Opportunities Program*</td>
<td>12</td>
<td>6 (50%)</td>
<td>3 (25%)</td>
</tr>
<tr>
<td>Graduate Students*</td>
<td>30</td>
<td>5 (17%)</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>Postdoctoral Associates*</td>
<td>13</td>
<td>3 (23%)</td>
<td>1 (8%)</td>
</tr>
<tr>
<td>Faculty</td>
<td>27</td>
<td>7 (26%)</td>
<td>2 (7%)</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>160</strong></td>
<td><strong>80</strong> (50%)</td>
<td><strong>15</strong> (9%)</td>
</tr>
</tbody>
</table>

# Includes two UMET students
* Numbers for these participant groups include students paid directly by the grant, as well as those who worked on MRSEC research for academic credit or were supported with other funds.
9. KNOWLEDGE TRANSFER TO INDUSTRY AND OTHER SECTORS

CMSE has a long-standing history of promoting collaboration with, and knowledge transfer to, industry. The many excellent CMSE-supported graduate students and postdocs who leave MIT to work in industry represent an important vehicle for knowledge transfer and workforce development. By emphasizing team-based, interdisciplinary research within the IRG groups, students and postdocs are trained in a mode that is critically important to meeting the complex, fast-moving challenges of industry. Indeed, the education and research programs at MIT have a proven track record for producing many industrial leaders.

**Industrial Knowledge Transfer:** CMSE works effectively with a number of MIT industrial programs and centers to facilitate the transfer of the fundamental knowledge generated within the MRSEC program to industry. MIT’s Materials Processing Center (MPC) and Industrial Liaison Program (ILP), for example, work cooperatively to connect industry to the research carried out within the MRSEC program. Over 195 multinational companies belong to the ILP, and 24 MIT industrial liaison officers who help to make connections to CMSE research serve these companies. The mission of the MPC, of which Prof. Carl Thompson is director, is to promote collaborations with industry and to foster the exchange of knowledge and the development of new knowledge. MPC currently has 8 member companies in the MPC Industry Collegium, 28 companies supported by the Microphotons Center, 12 academic affiliates, 7 roadmap organizations and national labs, and more than 100 participating roadmap study organizations. Members and invited participants are directly involved in one or more of the five Technology Working Groups created and managed by the center. MPC also maintains informal contact with more than 200 companies and is active with over 20 universities (8 international) in research and collaboration.

**Summary of Important Activities and Events:** In October 2015, CMSE plans to contribute to the MIT showcase materials event, the annual “Materials Day at MIT” program organized by the Materials Processing Center. Co-organizing the poster session enables CMSE to showcase MRSEC funded research and connect this research directly to managers and researchers from industry and government laboratories. All MRSEC supported researchers are encouraged to have group members contribute posters to this event. The title of this year’s Materials Day has yet to be determined.

Also this fall, CMSE will resume collaboration with the Department of Materials Science and Engineering and the Materials Processing Center to welcome a wide variety of speakers from outside of MIT to meet with CMSE faculty and students, and to deliver lectures to which the entire MIT community is invited. These lectures expect to draw audiences of 75-100 people. To promote inter-MRSEC interactions, we frequently invite researchers for other MRSECs to make presentations. This coming fall, three MRSEC directors plus two professors have agreed to give presentations. Speakers planned to present this fall include Arjun Yodh from the University of Pennsylvania; Michael Ward from New York University; Melissa Hines from Cornell University; Hui Cao from Yale University; and Alon Gorodetsky from the University of California, Irvine.

MRSEC-supported faculty presented an overview of their CMSE research in three ILP-sponsored conferences: the 2014 MIT Research and Development Conference in November 2014 (F. Brushett, S. Leeb, and T. Lu); the 2015 MIT Brazil Challenge of Innovation Conference (COI) in May 2015 (B. Olsen); and the 2015 MIT China Conference in Wuxi also in May 2015 (G. Chen and C. Ross). The 2014 MIT Research and Development Conference was attended by nearly 325 attendees and 340 individual representatives from companies including 3M, Accenture, BMW, Bose, Energizer, ExxonMobil, Fujifilm, GE, LG Electronics, Nestle, Pepsi, Novartis, P&G, Pfizer, Raytheon, Samsung, and Siemens. Co-organized with Fundação CERTI and SENAI of Brazil, the 3rd MIT COI united 11 world-renowned MIT faculty members, including
CMSE’s B. Olsen, with the 2015 Brazilian Congress on Industrial Innovation for two days of presentations and discussions on fostering innovation across industries. Held in Sao Paulo, Brazil, the event received over 460 attendees and explored a diverse range of topics — from management and manufacturing to energy, materials, agriculture, and automation — while it also provided a platform for building effective partnerships of mutual advantage with Brazilian commerce, one of the world’s fastest growing economies. The 2015 MIT China Conference in Wuxi, China, provided opportunities to engage 265 academics and global executives in driving national and global economic growth through innovation and entrepreneurship in advanced manufacturing, new materials, and energy solutions.

Additionally, independent of ILP, CMSE helped to sponsor the 89th American Chemical Society (ASC) Colloid and Surface Chemistry Symposium, a three-day event that took place in June on the Carnegie Mellon University campus. The symposium highlighted the latest scientific advances in colloid and surface science and its connection with a broad spectrum of scientific fields. Attended by 600 individuals in fields ranging from academia, industry, and national laboratories, the symposium welcomed a high presence of international participants from 20 countries who engaged in 11 parallel symposia, which included over 510 oral and poster presentations; a poster session; two plenary lectures; and an instrument exhibition. CMSE’s contribution to the event enabled the ASC to keep registration fees below the marginal cost per attendee, thus allowing a higher attendance rate of students to the event.

In June, K. Van Vliet participated in the Automation and the Internet of Things in Manufacturing which addressed the ongoing increase of interconnectivity with the evolution of the internet and its effect on industry in the startup faction. Hosted by the Startup Exchange at MIT, the workshop included presentations and a round of lightning talks among ILP member companies and MIT-connected startups and innovators who explored topics on the impending innovations, competition, challenges, trends and how technology and startup companies are, in turn, finding ways to navigate the internet.

Faculty Industry Meetings: To promote knowledge and technology transfer, the MIT ILP arranges meetings between MIT faculty and members from industry (both domestic and foreign). These meetings are typically hourly meetings held at MIT, full or half-day meetings at the company, or faculty briefings to a small group of technical managers from a single company or an industrial consortium. Such meetings often result in new research partnerships, new product or process development and/or consulting arrangements, all of which result in the transfer of CMSE fundamental knowledge to industry. During this reporting period, MRSEC faculty and/or their group members engaged in about 57 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 include: Ajinomoto Co., Inc.; Chevron Corporation; Eaton Corporation; Energizer-Schick / Energizer Personal Care; ExxonMobil; Honda R&D Co.; Natura; Saudi Basic Industries Corporation; Sekisui Chemical Company Ltd.; Shell; and Wuxi Sunshine Power. The CMSE director made presentations about this MRSEC to Chevron, Dai Nippon Printing, Total S.A., Illinois Tool Works, Shanghai Banzan Macromolecule Material Co., Samsung Electronics, and Hitachi Chemical Co.

MIT’s Technology Licensing Office (TLO) is kept aware of new discoveries emanating from CMSE research and helps researchers file patents and issue licenses. During this reporting period, 4 new patents have been issued and 6 new patent applications pending are related to the MIT MRSEC.
Another important mechanism for knowledge transfer is the creation of new companies and businesses (and related jobs). In previous grants, CMSE-related companies that were started by MRSEC faculty, students, or post-docs included OmniGuide Inc., LumArray, Luminus Devices Inc., QD Vision, Kateeva, and WiTricity Corporation. 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 MRSEC-related companies (OmniGuide, LumArray, Luminus Devices, QD Vision, Kateeva, and WiTricity) is over 400 jobs and growing. There have not been any new companies to date that have been developed since the start of this grant.

**Research Collaborations of IRGs:** The Center’s MRSEC-supported faculty enjoys a high level of outside collaboration. During the first nine months of this funding period, there were a total of 36 collaborations. These included 33 collaborations with outside academic researchers, 2 collaborations with government laboratories and agencies, and one collaboration with industry, all of which were MRSEC related. Out of those collaborations, 26 are international (see next section). 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. Specific IRG and Initiative collaborations are summarized below.

**IRG-I Collaborations:** Abouraddy joins with A. Dogariu from the University of Central Florida College of Optics and Photonics (CREOL, UCF) in researching optical scattering from photonic particles, and with D. Christodoulides, also from CREOL, UCF, to work with PT symmetric devices. Abouraddy also collaborates with T. Kottos of Wesleyan University in working with optical limiters. Anikeeva investigates tissue response to fiber probes with W. Shain of the University of Washington and Seattle Children’s Research Institute, and collaborates with C. Mortiz (University of Washington) on designing fiber probes for optical spinal stimulation of neural plasticity. Fink will leverage the expertise of H. Stone of Princeton University, and Z. Wang of the University of Texas at Austin. Stone contributes expertise in modeling and understanding of fluid motions dominated by viscosity; quantitative understanding of the flow phenomenon heat transfer and mass transfer problems involving convection; and diffusion and surface reactions associated with the fiber fluid instabilities. Wang provides expertise in biomedical engineering; electromagnetics & acoustics; plasma/quantum electronics and optics; and solid-state electronics. Joannopoulos and Soljačić collaborate with B. DeLacy (U.S. Army Edgewood Chemical Biological Center, ECBC) on the fabrication and characterization of nanoparticles.

**IRG-II Collaborations:** Ross collaborates with C. Ahn from Yale University, who supplies Si substrates with a thin SrTiO₃ layer which Ross’s research uses to integrate perovskite films on Si.

**Seed Collaborations:** Checkelsky discusses spin structures of Correlated Topological Phases with R. Chisnell of the National Institute of Standards and Technology of Gaithersburg.
10. INTERNATIONAL ACTIVITIES

Center-Facilitated Collaborations:

A number of new activities were launched with Professor Marisa Beppu at the U. Estadual de Campinas, São Paulo, Brazil. These included one visiting graduate student and one visiting post-doc, both supported by the Brazilian government. The visiting scholars, worked for 6 months at MIT on CMSE projects supervised by Professors Cohen and Rubner. In addition, Professor Beppu and a graduate student visited MIT for one week to use the CMSE SEFs. In another visit to MIT, Professors Beppu and Rubner met to discuss further activities including the exchange of students and post-docs in the near future.

IRG-related Collaborations: Fink and F. Sorin of École Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland unite in training students on multimaterial fiber production. Fink leverages the expertise of S. Danto from Université Bordeaux in France on amorphous semiconductors, specialty fibers, and phase-change materials. Fink also collaborates with D. Milanese from Polytechnic University of Turin in fluorescence microscopy experiments to study sphere breakup. Fink and Soljačić collaborate with M. Segev (Technion – Israel Institute of Technology) on nonlinear optics, solitons, sub-wavelength imaging, and lasers and quantum electronics. Johnson collaborates with Prof. Jean-Christophe Nave of McGill University in Montreal, Canada to employ semi-Lagrangian methods. Doyle collaborates with the Y. Jie of the National University of Singapore in building experimental systems for high force active microrheology. Grodzinsky maintains numerous collaborations that foster research on aggrecan in cartilage systems in both a provisional and intellectual capacity. A. Fosang of the University of Melbourne and the Royal Children’s Hospital in Australia provides Grodzinsky with a range of knee joint samples from uniquely generated mice, such as knock-outs for aggrecanase and collagenase. S. Lohmander of Lund University in Sweden provides access to cartilage tissue and to technology for analyzing aggrecan structure, biosynthesis, and enzymatic degradation. A. Struglics, also from the Lund University, joins Grodzinsky to focus on analyses of aggrecan fragments generated by proteolytic (aggrecanase) activity collected from knee synovial fluid samples. P. Önnerfjord, also from Lund University, collaborates with Grodzinsky in researching mass spec proteomics of cartilage matrix response to injury. Grodzinsky also collaborates with both A. Niehoff and F. Zaucke from the University of Köln in Germany on a type IX collagen knock-out to test for osteoarthritic-like degeneration of the knee cartilage. Holten-Andersen and M. Harrington from the Max Planck Institute of Colloids and Interfaces in Potsdam, Germany explore the mechano-chemistry of mussel holdfast materials. Olsen collaborates with M. Gibson from the University of Warwick on artificially engineered proteins for glycan arrays. Beach and S. van Dijken of Aalto University in Finland research in-situ TEM and EELS in their studies of cross-sectional structure and composition in thin-film heterostructures. Ross collaborates with J. Florez Uribe (Universidad Técnica Santa María, Valparaiso, Chile) in configuring density functional theory calculations. Ross joins with X. Sun of the Harbin Institute of Technology in China in their work on TEM of magnetic perovskites. Ross unites with T. Goto of Toyohashi University of Technology (TUT) in Japan in their work with magnetooptical measurements/devices, and with M. Inoue, also from the TUT, in integrating magnetic perovskites into optical devices. Ross also collaborates with M. Coey of Trinity College in Dublin, Ireland, in their work on Mossbauer measurements of our magnetic perovskites, and with M. Kläui from the University of Mainz in Germany to focus on PFM measurements of samples from IRG-III members. Van Vliet collaborates with J. Smith of Micro Materials in the United Kingdom to develop in-situ nanomechanic instruments. Yildiz studies with resistive switching materials with R. Waser of RWTH Aachen University in German and I. Valov of Forschungszentrum Jülich GmbH, also in Germany.
11. SHARED EXPERIMENTAL FACILITIES

The ongoing development and advancement of exceptional Shared Experimental Facilities (SEFs) is a key enabling component of the MIT MRSEC program. These facilities, which are housed in over 11,600 sq. ft. in the Vannevar Bush Building at MIT, have played a pivotal supportive role in many key science and engineering discoveries made at MIT. They include advanced tools for both materials characterization and processing. Many of the capabilities provided by the SEFs are unique such as a TEM fitted with a cathodoluminescence system. Decisions about equipment added to the SEFs are motivated by a desire to provide and maintain large sophisticated tools not readily available to individual investigators. The SEFs not only serve the MRSEC research program, but they continue to be an important resource to the broader materials community (both inside and outside MIT). From 2006 to the present, the number of individual users per year in our facilities has steadily increased from about 500 to well over 1,000. Typical users include MRSEC supported faculty and their students, other MIT investigators and their students, researchers from other universities, and non-profit and industrial organizations. A top priority is to continually upgrade and enhance the capabilities of our SEFs.

Summary of Important Activities during this Funding Period

Materials Research Facilities Network (MRFN) Participation: The MIT MRSEC continues to be an active participant in the Materials Research Facilities Network (MRFN). Participation in this network enables access to our facilities by researchers from other universities, particularly those with limited research tools and minority serving institutions. A process has been established that involves the submission of a short proposal outlining the analysis to be done and how the results will impact the proposer’s research program and, if relevant, educational activities. During the summer of 2015, Dr. Eugenia Ciocan, from Bunker Hill Community College, a participant in the 2015 CMSE RET program in Prof. Polina Anikeeva’s lab, will be using MRFN funding to complete her research in the CMSE EM and X-ray facilities. Prof. Ellie Fini from the North Carolina Agricultural and Technical State University will be using MRFN funds to complete work in the EM and X-ray facilities. In late May 2015 Prof. Oliva Primera-Pedroza, from Universidad Metropolitana in Puerto Rico, arranged for a graduate student and two undergraduate students to come to our labs to continue research, and Prof. Marisa Beppu, from U. Estadul de Campinas in Brazil, visited with a student to use our facilities. In addition, Prof. Maria Del C. Cotto Maldonado, from the Universidad del Turabo in Puerto Rico, plans another visit with a student in late August/early September 2015 to continue research started with her visit in August 2014.

SEF Management and Operation: Our SEFs are managed by a highly motivated and engaged professional team of seven full-time staff members, including four PhD-level scientists with strong research backgrounds. The SEF staff in each facility, under the direction of the director and assistant director, oversee the operation of the SEFs and make recommendations on SEF policy, staffing needs, and the elimination and addition of instrumentation. Faculty user groups are utilized as needed to identify critical capital equipment needs and to provide a critical assessment of facility and staff performance. An on-line feedback system that allows users to easily provide anonymous feedback about equipment, staff, and operations, as well as periodic user surveys are used to further assess SEF performance. The Coral facilities lab management system is utilized for online user registration, instrument booking, safety training validation, real time instrument status monitoring, and instrument billing.

SEF staff members are actively encouraged to participate in local or national meetings, publications, new technique and tool development, professional societies, or other professional growth opportunities. This ensures that they maintain state-of-the-art knowledge about new characterization tools and techniques and MRSEC relevant research developments. For example, Timothy McClure, Analytical SEF, attended a four-day ICP training at Horiba in New Jersey during May 2015. Dr. Shiahn Chen and Mr. Patrick Boisvert, EM SEF, attended a four-
day training course for the EDAX microscope attachment in June 2015. Dr. Charles Settens, X-ray SEF, will attend the Denver X-ray Conference in August 2015 to interact with suppliers and survey X-ray hardware, sources and detectors, in-situ sample stages and data analysis software packages, and Dr. Shiahn Chen, EM SEF, will attend the Microscopy Society of America annual meeting in Portland, Oregon during August 2015.

In order to coordinate major materials related equipment purchases at MIT, an MIT-wide Facilities Managers Group was established by the VP of Research. The director of CMSE chairs this institute level committee, which includes the managers of all key materials related shared facilities on campus (a total of 16 facilities). In addition to working to avoid instrument redundancy and to provide a diversity of critically needed tools at MIT, this committee meets periodically to review best operational practices and safety issues. A meeting of this committee was held on April 8, 2015, to discuss best practices in each lab, current equipment purchases, current use of the Coral lab management system and the impact of the construction of the new MIT.nano building on campus facilities.

The CMSE SEFs are an important resource to many users with no MIT affiliation. To access our facilities, such researchers must submit and have approved, a short application to CMSE detailing organizational, safety and project information. In the case of commercial organizations, the application is only approved if the SEFs provide capabilities that are not available commercially and the use is consistent with NSF Notice #122. The cost of purchasing and installing equipment is handled separately and is cost shared with MIT Schools and Departments whenever possible. No fee distinction is made between MIT users and those from other universities, teaching hospitals, or government laboratories and agencies. Commercial users, on the other hand, are charged higher fees as they are expected to cover the full cost of operations. The use of MRSEC supported facilities by small start-up companies and by commercial organizations with federal agency grants and contracts is encouraged and, as such, the center endeavors to maintain user fees at a reasonable level. We anticipate that about 90% of the operating costs of the facilities (staff salaries, materials and supplies, service contracts, etc.) will be covered by user fees.

**SEF Educational Activities:** The MRSEC SEFs and staff play a critically important role in the training and education of MIT graduate and undergraduate students, postdoctoral associates, CMSE educational outreach participants and visitors, as well as a wide range of outside academic and industrial researchers. Each of our SEF staff typically offers at least one mini-course during MIT’s Independent Activities Period (IAP) in January to educate students and post-doctoral associates about underlying theories, advanced analytical techniques and potential new applications of tools housed in our shared facilities. During January 2015, six courses were offered to the MIT community, but, due to extreme weather in New England, only four courses took place. CMSE facilities and staff are also an integral component of undergraduate laboratories taught by various MIT academic departments. About 180 to 200 undergraduate students per year typically use MRSEC facilities as part of their departmental laboratory subjects. SEF staff actively contribute to the ongoing development and implementation of the educational modules associated with these laboratories. This year users from 22 MIT departments, labs and centers, 11 outside academic units, and 12 outside commercial units used the CMSE SEFs.

<table>
<thead>
<tr>
<th>SEF users during the year ending 6/30/2015</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Students and staff from external academic/research inst.</td>
<td>36</td>
</tr>
<tr>
<td>Staff of external senior level industrial managers</td>
<td>20</td>
</tr>
<tr>
<td>Students from MIT lab subjects - estimated</td>
<td>180</td>
</tr>
<tr>
<td>Students and postdocs of MIT faculty</td>
<td>820</td>
</tr>
<tr>
<td><strong>Total Users</strong></td>
<td><strong>1,056</strong></td>
</tr>
</tbody>
</table>
**Current Shared Experimental Facilities:** The following facilities are an integral part of our proposed SEFs. Combined, these facilities house about 60 major materials characterization and processing tools.

**Materials Analysis:** This facility provides advanced surface analysis tools for the determination of elemental and chemical composition with high surface sensitivity and spatial resolution as well a variety of spectroscopic tools including: two atomic force microscopes; an x-ray photoemission spectrometer (XPS) with a C60 ion source for chemical depth profiling and a heating/cooling stage operating up to 500°C; a scanning Auger nanoprobe with 11 nm spatial resolution that can map surface potential, magnetic domains, electrostatic domains, conductivity and capacitance; an ellipsometer; a UV-Vis-NIR spectrophotometer; a fluorimeter; a Fourier transform infrared spectrometer with IR microscope attachment; a micro-Raman spectrometer; a surface stress measurement system; a profilometer; optical microscopes; an ICP-OES system for trace elemental analysis; a quartz crystal micro balance; and a spectroscopic ellipsometer.

**Electron Microscopy:** This facility provides advanced image analysis tools to examine the nano and micro-structures of materials including crystal structures and elemental composition. Specific equipment includes: one 200kV FEG-TEM/STEM with imaging filter; two 200kV TEMs, one equipped with a cathodoluminescence system; a 120kV TEM/STEM; a dual-beam SEM/FIB workstation with nano-scaled lithography capability; a high resolution FEG-SEM; an environmental FEG-SEM with a peltier stage; a general-purpose SEM; and specimen preparation and image analysis equipment.

**X-ray Diffraction:** This facility maintains a versatile suite of X-ray diffractometers and a fluorescence spectrometer to support a wide variety of research needs. Three of the diffractometers are specialized units, while two are multipurpose instruments that provide access to a variety of optics and sample stages. Specific equipment includes: two high-speed powder diffractometers; a high-resolution triple-axis diffractometer; an area-detector enabled diffractometer with microdiffraction, spatial mapping, and in-situ capabilities; a multipurpose diffractometer for parallel-beam or high-speed diffraction with in-situ capabilities; SAXS; back-reflection Laue diffractometer; three SQUID magnetometers; and a hand-held XRF.

**Nanostructured Materials Growth and Metrology Facility:** This new energy focused materials processing and characterization facility was launched with the aide of an NSF ARRA grant that supported the renovation of 2,900 sq. ft. of laboratory space. Equipment includes: an AFM; an inspection optical microscope; a 4-point probe device; a He cryostat; a Ti-Sapphire laser and tunable laser source; an IR light source and monochromater; a streak camera for visible light signals; an 85% humidity/85 degrees environmental chamber; a 3D imaging Veeco Dektak; a multi-glove box system containing a solar simulator system; an I-V and C-V testing set-up; a multi-source thermal evaporator; and a spin-coater.

**Proposed additions to Shared Experimental Facilities:** Based on current input from faculty and users, we anticipate adding the equipment highlighted below to the SEFs. All proposed equipment purchases, however, are reviewed and prioritized by our Internal Advisory Committee (IAC). Final decisions about equipment purchases are made only after a careful vetting process involving MIT faculty and user input and consideration of MRSEC research objectives and unanticipated opportunities that might arise.

Major equipment currently under consideration:

Time-of-flight secondary ion mass spectrometer (SIMS)
Upgraded small angle x-ray scattering unit (SAXS).
Overview and Broader Impact: MIT enjoys the benefit of a large and wide-ranging materials science and engineering community: about 200 faculty and senior staff from 11 different departments, labs, and centers. A key objective of our proposed MRSEC is to engage this community and enable collaborations and activities that result in unique to center high impact science and engineering, effective educational outreach programs and successful knowledge transfer to industry. The CMSE director currently reports directly to the dean of engineering (see organizational chart at end of section). This is a temporary arrangement until the new MIT-Nano Building is completed, at which point the CMSE director will again report directly to the VP of Research. The mission of the MRSEC remains the same: To encourage faculty from different departments and schools to work together on complex problems that require an interdisciplinary research approach.

Significant Activities of Period 1: MIT has started construction on the new MIT-Nano building that is expected to open in 2018. The director of CMSE is a key member of the committee charged with working out the design of the building and establishing a suitable management structure. This new building will house primarily shared experimental facilities including the CMSE Electron Microscopy, X-ray and Surface Analysis labs and the Microsystems Technology Laboratory (MTL) facilities.

Space Management and Organizational Synergies: CMSE controls the research and office space of the Vannevar Bush Materials Science and Engineering Building (Building 13 – ca. 60,000 square feet of laboratory space), thereby providing a powerful mechanism for encouraging collaborative research and creating/maintaining state-of-the-art SEFs. Departments at MIT are responsible for the hiring of new faculty, however, CMSE works closely with MIT departments to recruit and develop new talent with expertise in areas that support the MRSEC long-term mission with a focus on women and underrepresented minorities. Close synergistic coupling to organizations at MIT charged with the important mission of engaging industry in MIT research, MIT’s Materials Processing Center (MPC) and Industrial Liaison Program (ILP), is used to promote effective knowledge transfer and gain valuable industrial input, guidance, and collaboration.

Seed Competition: The objective of our seed funding program is to 1) move the MRSEC program in new directions, 2) encourage participation from junior faculty as well as women and underrepresented minorities, and 3) identify and act quickly on new, high risk, and potentially high-impact research opportunities. To this end, we have developed a streamlined process for seed selection. Seed proposals are solicited from the entire MIT community, reviewed and ranked by our internal advisory committee and awarded to the four most competitive proposals per seed cycle. All faculty proposing a seed are encouraged to meet with the MRSEC director prior to submission to discuss the overall mission of the center, current research activities within IRGs, how to prepare the most competitive seed proposal, and educational outreach opportunities. Seed recipients are also invited to meet with IRG leaders of research groups that best align with their proposed research. Each seed project will be funded for up to two years. Progress of seeds towards their objectives will be evaluated on a yearly basis. For our first seed competition, we received 14 proposals from five different MIT departments; all but one was received from assistant professors. The four seed proposals approved and currently active include one women and one minority.

Center Management: The administrative staff of the MRSEC includes the following full time personnel: an assistant director, an education officer, a financial administrator, a facilities/safety coordinator, and one administrative assistant. The director and assistant director are responsible for the overall management of the center. The education officer coordinates the educational programs and important special projects; the financial administrator coordinates accounting and business functions; the facilities/safety coordinator oversees issues related to
lab renovations, space changes and safety; the administrative assistant provides operational support. The facilities/safety coordinator position has enabled the center to more effectively manage the Bush Building and the facility needs of MRSEC researchers. Our educational outreach programs are developed, organized, and nurtured by two MIT faculty members: our faculty education leader, S. Leeb; and our faculty special projects coordinator, A. Belcher.

Advisory Committees: Three internal MIT committees and one external committee provide guidance to the director. The CMSE Science and Engineering External Advisory Board (SEEAB) provides advice from an external perspective. This committee is composed of leaders of industrial, university, and government laboratories that support major efforts in long-range materials research and engineering (see below). The Internal Advisory Committee (IAC) advises the director about all major decisions involving CMSE including major equipment purchases and seed funding selection. The IAC is composed of the leaders of each of the IRGs, as well as the faculty education leaders and shared facilities manager. The CMSE Space Committee advises the director about major decisions involving the operation and space allocation of the Bush Building; ensuring that space is appropriately allocated for MRSEC research (and the broader materials community) based on research needs and intellectual relevance. An Executive Oversight Committee, currently led by the Dean of the School of Engineering with input from the Dean of the School of Science, provides the broader MIT perspective and facilitates connections to related MIT-wide initiatives, such as the MIT diversity and post-doc mentoring programs. Our SEEAB typically meets annually to review progress of the center, evaluate the quality and impact of our research and outreach programs and provide guidance about ways in which collaboration between CMSE and other academic, national and industrial laboratories can be enhanced. The following individuals currently serve on our SEEAB: Dr. Leonard Buckley, Director, Science and Technology Division (Institute for Defense Analyses); Dr. Edwin Chandross, Materials Chemical Consultant (formerly Bell Labs, Lucent Technologies); Dr. James Misewich, Associate Laboratory Director for Basic Energy Sciences (Brookhaven National Lab); Dr. Rama Bansil, 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.
<table>
<thead>
<tr>
<th>Student Name</th>
<th>Student Dept.</th>
<th>Thesis Title/Graduation Date</th>
<th>Supervisor/Dept.</th>
<th>Employer/Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perli Samuel</td>
<td>EECS</td>
<td>An Integrated CRISPR-Cas</td>
<td>T.K. Lu / EECS</td>
<td>MIT Cambridge, MA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toolkit for Engineering</td>
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<td>Human Cells</td>
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<td></td>
<td></td>
<td>June 2015</td>
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<tr>
<td>Onbasli Mehmet</td>
<td>DMSE</td>
<td>Magneto-Optical and</td>
<td>C.A. Ross / DMSE</td>
<td>Corning, Inc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiferroic Oxide Thin Films,</td>
<td></td>
<td>New York, NY</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integrated Nonreciprocal</td>
<td></td>
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<td></td>
<td></td>
<td>Photonic Devices and</td>
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<tr>
<td></td>
<td></td>
<td>Multiferroic Memory Devices</td>
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<td></td>
<td></td>
<td>June 2015</td>
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*Underrepresented Minority
**Female
<table>
<thead>
<tr>
<th>Postdoc Name</th>
<th>Department</th>
<th>Current Employer/Location</th>
<th>Supervisor</th>
<th>Support Agency</th>
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</thead>
<tbody>
<tr>
<td>Lu</td>
<td>Physics</td>
<td>MIT Cambridge, MA</td>
<td>M. Soljačić</td>
<td>DOE / DOD / CMSE</td>
</tr>
<tr>
<td>Chen</td>
<td>DMSE</td>
<td>Banzan International Group Corporation Cambridge, MA</td>
<td>H. Tuller</td>
<td>DOE / COFFEI / CMSE</td>
</tr>
<tr>
<td>Chen</td>
<td>BioE</td>
<td>unknown</td>
<td>K. Ribbeck</td>
<td>RLE Postdoctoral Translational Fellows Program / CMSE</td>
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* Underrepresented Minority
** Female
14. SUPPORTED PUBLICATIONS
November 2014 – July 2015

IRG-I: Harnessing In-Fiber Fluid Instabilities for Scalable and Universal Multidimensional Nanosphere Design, Manufacturing, and Applications
Partial MRSEC support that acknowledge the MRSEC award – less than 50% of support from MRSEC


IRG-II: Simple Engineered Biological Motifs for Complex Hydrogel Function
Primary MRSEC support that acknowledge the MRSEC award – approximately 50% or more support from MRSEC


IRG-III: Nanoionics at the Interface: Charge, Phonon, and Spin Transport
Partial MRSEC support that acknowledge the MRSEC award – less than 50% of support from MRSEC


No direct MRSEC support but research and subsequent publication directly impacted by use of shared facilities.


Huang, A., Qin, G., and Olsen, B.D. “Highly active biocatalytic coatings from protein-polymer diblock copolymers.” ACS Applied Materials & Interfaces, 7(27): 14660-14669, July 2015. <DOI: 10.1021/acsami.5b01884>


Ma, W. Kim, J.J., Tsvetkov, N., Kuru, Y., Cai, Z., Chen, Y., Tuller, H.L., and Yildiz, B. “Vertically aligned nanocomposite La$_{0.8}$Sr$_{0.2}$CoO$_3$/(La$_{0.5}$Sr$_{0.5}$)$_2$CoO$_4$ cathodes – electronic structure, surface chemistry and oxygen reduction kinetics.” Journal of Materials Chemistry A, 3: 207-219, 2015. <DOI: 10.1039/C4TA04993D>


Publications that acknowledge support from previous NSF MRSEC award, DMR 08-19762, that were not previously published at the time of submission of the last report

IRG-I (DMR 08-19762): Electrochemical Energy Storage and Conversion

Primary MRSEC support that acknowledge the MRSEC award – approximately 50% or more support from MRSEC.


Partial MRSEC support that acknowledge the MRSEC award – less than 50% of support from MRSEC

Kim, J.C., Seo, D.H., and Ceder, G. “Theoretical capacity achieved in a LiMn_{0.5}Fe_{0.4}Mg_{0.1}BO_3 cathode by using topological disorder.” *Energy & Environmental Science*, 8(6): 1790-1798, 2015. <DOI: 10.1039/c5ee00930h>


**IRG-II (DMR 08-19762): Mechanomutable Heteronanomaterials**

Primary MRSEC support that acknowledge the MRSEC award – approximately 50% or more support from MRSEC


Partial MRSEC support that acknowledge the MRSEC award – less than 50% of support from MRSEC


**IRG-III (DMR 08-19762): Nano-Structured Fibers**

Primary MRSEC support that acknowledge the MRSEC award – approximately 50% or more support from MRSEC


**Initiative-I (DMR 08-19762): High Def Nanomaterials**

Primary MRSEC support that acknowledge the MRSEC award – approximately 50% or more support from MRSEC.

Polak, R., Bradwell, G.M., Gilbert, J.B., Danielsen, S., Beppu, M.M., Cohen, R.E., and Rubner, M.F. “Optimization of amine-rich multilayer thin films for the capture and quantification of

No direct MRSEC support but research and subsequent publication directly impacted by use of shared facilities (DMR 08-19762)


Han, B.H., Qian, D.N., Risch, M., Chen, H.L., Chi, M.F., Meng, Y.S., and Shao-Horn, Y. “Role of LiCoO₂ surface terminations in oxygen reduction and evolution kinetics.” *Journal of Physical Chemistry Letters*, 6(8): 1357-1362, April 2015. <DOI: 10.1021/acs.jpclett.5b00332>


* Current investigator who incorrectly acknowledged the former award number DMR 08-19762.
## 14. PATENTS APPLIED FOR AND ISSUED UNDER NSF SUPPORT
### November 2014 to July 2015

<table>
<thead>
<tr>
<th>Faculty Names</th>
<th>Patent Title</th>
<th>Patent #/Date</th>
<th>Source of Support</th>
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<tbody>
<tr>
<td>U. Bauer, G.S. Beach</td>
<td>Methods, materials and systems for voltage programming material properties</td>
<td>Applied March 16, 2015</td>
<td>x</td>
</tr>
<tr>
<td>U. Bauer, G.S. Beach</td>
<td>Voltage-controlled solid state magnetic devices</td>
<td>Applied March 16, 2015</td>
<td>x</td>
</tr>
<tr>
<td>Y. Fink, B.J.B. Grena</td>
<td>Thermally-drawn fiber including porosity</td>
<td>Applied Feb. 17, 2015</td>
<td>x</td>
</tr>
<tr>
<td>P. Chen and N. Holten-Andersen</td>
<td>Multi-simuli-responsive white luminescent materials using hybrid lanthanide metal-coordinate complex probes</td>
<td>Applied Dec. 2, 2014</td>
<td>x</td>
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<tr>
<td>O. Shapira, B. Zhen, S.L. Chua, J. Lee, J.D. Joannopoulos, M. Soljačić</td>
<td>Excitation enhancement and extraction enhancement with photonic crystals</td>
<td>U.S. Patent 8,969,831 Issued March 3, 2015</td>
<td>x</td>
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<tr>
<td>A.I. Akinwande, Y.W. Choi, I.D. Kim, H.L. Tuller</td>
<td>Fabrication of electronic and photonic systems on flexible substrates by layer transfer method</td>
<td>U.S. Patent 9012992 Issued Apr. 21, 2015</td>
<td>x</td>
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<tr>
<td>Q. Lu, N. Tsvetkov, B. Yildiz</td>
<td>Segregation resistant perovskite oxides with surfaces modified by binary oxides and heterogeneous doping</td>
<td>Applied March 24, 2015</td>
<td>x</td>
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</table>
15. BIOGRAPHIES

There is no new information to add during this reporting period.
### 16. CENTER PARTICIPANTS’ HONORS AND AWARDS
November 1, 2014 to July 31, 2015

<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Award</th>
<th>Awarding Organization</th>
<th>Award Date</th>
<th>Related to MRSEC?</th>
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<tbody>
<tr>
<td>A. Abouraddy</td>
<td>Monolithic multimaterial buoyant optical fiber cable</td>
<td>DARPA</td>
<td>March 2015</td>
<td>No</td>
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<tr>
<td>A. Abouraddy</td>
<td>2015 Research Incentive Award (RIA), University-wide</td>
<td>NSF</td>
<td>April 2015</td>
<td>Yes</td>
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<tr>
<td>A. Abouraddy</td>
<td>PFI: AIR-TT Robust infrared multimaterial chalcogenide optical fibers</td>
<td>NSF</td>
<td>April 2015</td>
<td>No</td>
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<tr>
<td>G. Chen</td>
<td>2nd Place- Poster Award- International Mechanical Engineering Conference and Exposition- Micro/Nano Forum</td>
<td>American Society of Mechanical Engineers</td>
<td>November 2014</td>
<td>Yes</td>
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<tr>
<td>G. Chen</td>
<td>Institute of Advanced Studies Distinguished Seminar</td>
<td>Hong Kong University Science &amp; Technology</td>
<td>January 2015</td>
<td>No</td>
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<tr>
<td>G. Chen</td>
<td>Institute of Advanced Studies Distinguished Seminar</td>
<td>Hong Kong University Science &amp; Technology</td>
<td>January 2015</td>
<td>No</td>
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<tr>
<td>G. Chen</td>
<td>Top 10 World Changing Ideas- Batteries that Capture Low Grade Waste Heat</td>
<td>Scientific American Magazine</td>
<td>December 2014</td>
<td>No</td>
</tr>
<tr>
<td>G. Chen</td>
<td>Academician – For pioneering contributions in understanding heat transport and demonstration of enhanced near-field thermal radiation heat transfer beyond the Planck law by three orders of magnitude; leading to significant advances in energy related materials and technology.</td>
<td>Academia Sinica Taiwan</td>
<td>July 2014*</td>
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*Not previously reported
### 16. CENTER PARTICIPANTS' HONORS AND AWARDS
#### November 1, 2014 to July 31, 2015

<table>
<thead>
<tr>
<th>Name</th>
<th>Award Description</th>
<th>Organization</th>
<th>Month</th>
<th>Previously Reported</th>
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<tr>
<td>P. Doyle</td>
<td>Robert T. Haslam 1911 Chair</td>
<td>MIT Chemical Engineering</td>
<td>November 2014</td>
<td>No</td>
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<tr>
<td>P. Hammond</td>
<td>The Alpha Chi Sigma Award for Chemical Engineering Research, AIChE Institute Award 2014</td>
<td>AICHE</td>
<td>April 2015</td>
<td>Yes</td>
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<tr>
<td>N. Holten-Andersen</td>
<td>Office of Naval Research Young Investigator Award</td>
<td>Office of Naval Research</td>
<td>April 2015</td>
<td>Yes</td>
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<tr>
<td>T. Lu</td>
<td>2015 Biochemical Engineering Journal Young Investigator Award</td>
<td>Editors of Biochemical Engineering Journal, in cooperation with ECI's Biochemical and Molecular Engineering XIX Conference</td>
<td>July 2015</td>
<td>Yes</td>
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<tr>
<td>B. Olsen</td>
<td>DuPont Young Investigator Award</td>
<td>DuPont</td>
<td>May 2015</td>
<td>No</td>
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<tr>
<td>B. Olsen</td>
<td>Chemical and Engineering News Top 12 Young Chemists</td>
<td>Chemical &amp; Engineering News</td>
<td>July 2015</td>
<td>Yes</td>
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<tr>
<td>B. Olsen</td>
<td>ACS Mark Young Scholar Award</td>
<td>ACS POLY Division</td>
<td>August 2015</td>
<td>Yes</td>
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<tr>
<td>B. Olsen</td>
<td>Camille Dreyfus Teacher-Scholar Award</td>
<td>Dreyfus Foundation</td>
<td>February 2015</td>
<td>Yes</td>
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<tr>
<td>Y. Surendranath</td>
<td>Toyota Young Investigator Award</td>
<td>The Electrochemical Society</td>
<td>July 2015</td>
<td>No</td>
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<tr>
<td>Y. Surendranath</td>
<td>Young Investigator Award</td>
<td>Air Force Office of Scientific Research</td>
<td>April 2015</td>
<td>No</td>
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<tr>
<td>Y. Surendranath</td>
<td>Young Investigator Award</td>
<td>Department of Energy</td>
<td>August 2015</td>
<td>No</td>
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<tr>
<td>Y. Surendranath</td>
<td>CAREER Award</td>
<td>National Science Foundation</td>
<td>March 2015</td>
<td>No</td>
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<tr>
<td>B. Yildiz</td>
<td>Best Poster Award at the International Solid State Ionics Meeting</td>
<td>International Solid State Ionics Society</td>
<td>June 2015</td>
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*Not previously reported
17. HIGHLIGHTS

The following four pages include MIT CMSE highlights during this funding period.
17. Creating crystalline silicon core fibers from aluminum and glass preforms
Y. Fink and J. Joannopoulos (IRG I)

Crystalline silicon is a critically important electronic material in all consumer electronic products. The ability to create fibers from this material would open up exciting vistas for a new generation of fiber-based electronic and optical devices. Traditional fiber-optic drawing involves a thermally mediated geometric scaling where both the fiber materials and their relative positions are identical to those found in the fiber preform. To date, all thermally drawn fibers are limited to the preform composition and geometry.

MIT MRSEC researchers have demonstrated (see figure) that it is possible to fabricate a meter-long crystalline silicon-core, silica-cladded fiber from a preform that does not contain any elemental silicon but rather aluminum and silica (glass). The ability to produce crystalline silicon core fibers out of inexpensive aluminum and glass paves the way for a simple and scalable method of incorporating silicon-based electronics and and photonics into fibers.

Figures: a, schematic of aluminum-core-quartz-cladding preform drawn into Silicon-core fiber. b, the chemical reaction at the core-cladding interface. Al atoms (blue) break Si-O bonds, reduce Si (black), release O$^2-$ ions (red), and change to Al$^{3+}$ ions (green). All the products of ions and atoms dissolve in the Al melt and diffuse into the core. c, the Si atoms (black), because of their miscibility, diffuse and remain in the Al melt (blue), while ions of O and Al form Al$_2$O$_3$ molecules (yellow) and precipitate out at the bottom. d-g, the SEM and EDX analysis on cross section of the Si-core fiber. Scale bar: 100 µm in d, 50 µm in e-g.

This work was supported in part by the MIT MRSEC through the MRSEC Program of the National Science Foundation under award number DMR-1419807.
Bio-Inspired Gels show promise as self-healing materials with properties controlled by metal ions, J. Johnson and N. Holten-Andersen (IRG II)

Nature has evolved numerous mechanisms for the self-healing of damaged tissues and structures. MIT MRSEC researchers have shown first successes in establishing a new class of smart polymer materials with controllable network junctions by combining Diels-Alder reactions with bio-inspired metal coordinate crosslinking to generate multi-functional polymers capable of self-assembly into and onto nano-structures with tunable properties (see Figure). Specifically, by decorating polymer backbones with ligands known to self-assemble into well-defined metal-coordinated geometric shapes or with ligands known to bind onto metal nanoparticles with tunable adhesive energy, this collaborative research has led to the assembly of materials with kinetically controllable crosslink junctions. With polymer material assembly now directly controlled via network junction kinetics and material mechanics dependent on measurable network junction structural dynamics, this effort has established an ideal platform upon which to explore the function of simple engineered bio-inspired motifs in complex hydrogel properties such as self-healing, controllable energy dissipation and remote-controlled transport.

This work was supported in part by the MRSEC Program of the National Science Foundation under award number DMR-1419807.
Strain coupling in oxide nano-composites controls magnetism and oxygen exchange kinetics, B. Yildiz and C. Ross (IRG III)

Two phase oxide nano-composites are made of two different materials grown together in a thin film, so the properties of the nanocomposite, such as magnetism, electronic conductivity, ionic conductivity, and catalytic activity, differ from those of their single phase constituents. More importantly, the properties of the two phases are coupled. This makes it possible to use an external field, like a magnetic field, to affect the properties of one phase, and indirectly affect those of the other phase.

MIT MRSEC researchers have created a nano-composite composed of a magnetic phase, (CFO, CoFe$_2$O$_4$) together with another phase of LSC or BSCF (La$_{0.8}$Sr$_{0.2}$CoO$_3$ or Ba$_{0.5}$Sr$_{0.5}$Co$_{0.8}$Fe$_{0.2}$O$_3$). LSC and BSCF are two of the most widely studied mixed electronic and ionic conductors which have fast oxygen exchange kinetics important for fuel cells.

These are the first nanocomposites made in this system, and offer the promise of being able to control conductivity and oxygen exchange reactivity of the perovskites by applying a magnetic field to strain the CFO phase.

Electron microscope image of CFO/BSCF and CFO/LSC showing crystals of the two phases grown together.

Oxygen exchange reaction is important for:

- Solid oxide fuel cells
- Red-ox based memristors

This work was supported primarily by the MRSEC Program of the National Science Foundation under award number DMR-1419807.
CMSE’s Felice Frankel and Nature’s Creative Director engage a global community of scientists and engineers in their live webcast discussion on graphics and photography

On July 21, 2015, CMSE and MIT’s edX sponsored a live global webcast where CMSE Research Specialist, Felice Frankel, conducted a one-hour online conversation on cover art and graphics with Kelly Krause, Creative Director of Nature magazine. Advanced promotion was distributed to the 8700 registered students of Frankel’s edX online course, “Making Science and Engineering Pictures, A Practical Guide to Presenting Your Work” along with the 1 million members of the edX distribution list. Seats were made available to the MIT community. The conversation concluded with questions received via twitter.

The recorded webcast, is available to review at: http://webcast.amps.ms.mit.edu/sum2015/ODL/1530/2.

This work was supported primarily by the MRSEC Program of the National Science Foundation under award number DMR-1419807.