Introduction & History

The Center for Nanoscale Science exploits unique capabilities at Penn State and partner institutions in materials synthesis, fabrication, and assembly, physical property measurements, computation and theory to make and organize nano-materials in configurations that can attain new regimes of properties and functionality. Interdisciplinary teams attack problems in strain and layer enabled multiferroics, powered nano-scale motion, the behavior of electrons in one-dimensional materials, and the control of light in nanostructures, Center activities involve forty eight students and post-doctoral fellows, thirty nine faculty from nine academic departments, and a number of external academic and industrial partners.

The Center was established in 2000 as a single Interdisciplinary Research Group, Center for Collective Phenomena in Restricted Geometries (DMR 0080019). In 2002, the Center merged with a new MRSEC, Center for Molecular Nanofabrication and Devices (DMR 0213623) comprising two IRGs: Chemically Advanced Nano-lithography (IRG1) and Nanoscale Motors (IRG2). The two MRSECs then merged. In 2004–05, the original IRG phased out its effort in fluids and polymers and split into IRG3 (Electrons in Confined Geometries) and IRG4 (Electromagnetically Coupled Nano-structures). In 2007, a new IRG on Strain Enabled Multiferroics, which grew from a seed project, was added as IRG5. In 2008, the Center was competitively re-newed as a four-IRG MRSEC (DMR 0820404), in which Chemically Advanced Nanolithography phased out and Strain Enabled Multiferroics became the new IRG1.

Currently, the four IRGs investigate emergent behavior of nanoscale systems with common themes of new materials synthesis and nano-fabrication, theory-led design, and length scale-dependent physical phenomena. The scientific programs of the IRGs are complemented by a highly competitive Seed program. The Seed program has played a major role in the scientific evolution of the Center, supporting junior faculty and high risk projects. Seed grants typically support 1 to 3 graduate students over ~18 months. The Seed program leverages funding from the Penn State Materials Research Institute (MRI) the Huck Institutes for the Life Sciences, and the Penn State Institutes for Energy and the Envi-

IRG1, Atomic Scale Design of Multiferroics, focuses on new phenomena multiferroic materials in which two or more ferroic (ferroelectric, ferroelastic, magnetic) order parameters co-exist within a single material. Precise tuning is imparted by control of strain, layer stacking, gradients, and exploitation of roto symmetries. Our expertise spans from first principles and phase-field modeling predictions of new materials and phenomena, to synthesis, structural electrical, magnetic, and optical characterization, and prototype devices. Recently, the IRG has predicted and discovered new metastable states of strong piezoelectric response, a strong spin-phonon ferroelectric ferromagnetic, highly tunable dipole-spring ferroics, and other systems with new physical properties.
The Center has initiated a new IRG-level Seed in 2011 on defect engineering in 2D structures, in addition to reconfiguring each of the existing IRGs through a competitive IRG Redirection Seed program.

**Education & Outreach**

During the past year, the MRSEC has continued to offer a range of educational outreach activities at the elementary, high school, college, and post-college levels. The majority of MRSEC faculty and graduate students have participated in at least one educational outreach program within the last year. These programs have reached approximately 3,000 K-12 students, 5 K-12 teachers, 18 undergraduates, and 100,000 visitors to science museums over the past year. The Center’s K-12 programs increase interest in science and build confidence, with special attention towards including girls and under-represented minority children.

In collaboration with the Franklin Institute, the Center deployed a fourth museum kit/show focusing on energy materials, and has begun development of a fifth kit/show. In addition, through the Franklin’s partnership with the Science Leadership Academy, a science magnet school in Philadelphia, the MRSEC recruits high school students into our Science Leadership summer camp.

The MRSEC has increasingly served as a hub K-12 outreach activities at Penn State. The Center has continued to develop content, provide staff support, and support scholarships for members of under-represented groups to attend summer science camps through the Science-U program at Penn State. Two new camps were offered, and the Science Leadership camp mentioned above expanded in its second year.

The Center continues to foster active involvement of undergraduates and high school

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**IRG2, Powered Motion at the Nanoscale**, designs, fabricates, measures and models molecular and nanoscale motors to address one of the grand challenges in science and engineering, namely, to master energy transduction and information on the nano- and microscale to ultimately create new technological capabilities that rival those of living things. The IRG synthesizes and studies of a range of molecular and nanoparticle-based motors that are driven by external fields, acoustic energy, and chemical reactions. Recently, we have discovered that enzyme diffusion is enhanced in the presence of substrate and can chemotax up a gradient: this novel source of motility may be present across a diverse range of systems, including biological systems.

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**IRG3, Charge and Spin Transport in Quasi-1D Nanowires**, brings together complementary expertise to explore new phenomena and critically examine issues related to charge and spin transport in quasi-1D metallic, superconducting, and magnetic nanowires and nanowire junctions, phenomena that encompass low dimensional condensed matter physics, materials growth and processing, and device design and fabrication.

Recently, the IRG has observed for the first time individual quantum phase slip events in a one-dimensional superconductor. IRG3 is initiating a new thrust on ultra-long quantum wires within optical fibers.
teachers through its REU/RET site, which is jointly run with the Penn State Physics Department. Representation from women and minorities in the REU and RET programs continues to significantly exceed national benchmarks. Through its Diversity Committee, the Center joins forces with relevant departments, colleges, and minority-focused organizations at Penn State in fostering exchange of faculty and recruiting graduate students from minority-serving institutions. The Center is continuing to benefit from mutual visits and scientific ties with partner minority-serving institutions in Texas and Puerto Rico.

The Center employs a number of postdoctoral fellows as researchers whose activities span several projects within the IRGs, and also as coordinators of education and outreach activities. The education-outreach postdocs are supported in multifaceted career-development activities, including teaching and proposal preparation.

**Knowledge Transfer & International Collaborations**

The outreach and knowledge transfer of the Center is driven primarily through research collaborations between its members with scientists and engineers in industry and national laboratories. One of the important vehicles for collaboration with industry is the MRSEC's Industrial Affiliates Program, now in its fifth year, with corporate members who jointly support the work of students in the Center. Further research is supported by industrial consortia or in partnership with startup companies. In addition to research collaborations, MRSEC faculty play a leading role at Penn State in organizing industrial workshops, making presentations at workshops and conferences, and participating in industrial fellowships and internships. The MRSEC also hosts a number of visiting scientists and is a strong component of the overall industrial/technology transfer infrastructure of the University. There is also strong international component to collaborative research and outreach activities of the Center.

**Management**

The management structure centers around the Executive Committee, Director, Associate Director and the IRG leaders with well-defined responsibilities as outlined in later sections. The Director reports regularly to the Executive Committee and the Vice President for Research, and consults with the directors of the Penn State Institutes (MRI, PSIEE, Huck). The Executive Committee meets about once a month, often after the Monday lunch seminars to discuss scientific progress

IRG4, *Electromagnetically Coupled Nanostructures*, integrates metals, semiconductors, and dielectrics on subwavelength scales to access new optical and optoelectronic material properties and novel devices. Using high-pressure fluid deposition (developed in the IRG), fiber pore arrays are filled by semiconductors and metals with nanometer-scale precision over meter lengths, including the recent fabrication of the first low-loss void-free ZnSe fiber cores suitable for hosting transition metal dopants, an advance highlighted by Nature in early 2011. Planar metallo-dielectric nanostructures are modeled and fabricated to access novel E-M scattering properties, including low, zero, and negative refractive index. The IRG has also begun to explore using high-pressure synthesis techniques in the planar platform.
of the various projects, review requests for substantial resource allocation, and discuss optimal strategies to maintain constant growth and renewal of our research and outreach missions. The Executive Committee oversaw the Seed review described earlier, and spearheaded preparations for the NSF panel review.

The Penn State MRSEC is advised by an external Advisory Board, which visits bi-annually, alternating with NSF-appointed site visit teams. Since an NSF site visit occurred in Spring 2012, the composition of the most recent external review committee was determined by NSF. These annual reviews provide a valuable external assessment of the scientific direction and administrative structure of the Center.

Central Facilities Laboratory
The MRSEC maintains a Central Facilities Laboratory, centrally located for easy access to all members of Center. The CFL has acquired instrumentation to serve the research needs of the four IRGs, and its facilities dovetail with the more extensive facilities of the Penn State Materials Characterization Laboratory (MCL).

The Center receives supplemental funding from DMR as part of the Materials Research Facilities Network (MRFN) to support a one-day characterization workshop and a summer faculty internship program that are intended to increase the participation of faculty and students from predominantly undergraduate and minority-serving institutions in the region. These activities leverage the full suite of characterization and fabrication tools available in the CFL and MCL.

Key Accomplishments

Intellectual Merit. The Penn State MRSEC is pleased to report a number of exciting scientific accomplishments within the past year. Space limits prevent a thorough summary here: please refer to the detailed writeups.

In the multiferroics project of IRG1, several important discoveries were made. In research on strain-enabled multiferroics in simple perovskites, the IRG team has further developed theory and experiment of a strong ferroelectric ferromagnet through spin-phonon coupling, observed strain-enabled multiferroic phase transitions and discovered metastable states with large piezoelectric response. In work on materials that are driven by layering, rotations and gradients, the team has found ferroic coupling in Ruddlesden-Popper layered structures, fully coupled polarization and magnetism in hybrid improper multiferroics, polar structures from non-polar building blocks, and highly tunable dipole spring ferroics in layered structures.

IRG2 has developed the theory of chiral diffusion and applied it to understand the motion of nanorotors produced by the experimental team. Enhanced diffusion and chemotaxis have been demonstrated in two distinct enzyme systems, a new source of motility not previously recognized. A new motor free energy source has been developed: acoustically powered motors, at both the 100 micron and 1 micron scales. De-polymerization powered pumps have been discovered/designed, and possible applications of nanopump mechanisms to oil recovery are being explored with industrial partners.

There have been several exciting advances in the area of charge and spin transport in quasi-ID nanostructures in IRG3. The IRG has developed a new family of core/shell semiconductor/ferromagnet nanowires. Significant progress towards identification of triplet superconductivity in cobalt/tungsten nanowire systems has been achieved. The
mechanism for the antiproximity effect has been clarified. And the IRG has made to our knowledge the first direct observation of what appear to be individual quantum phase slips in one-dimensional superconductors. In preliminary work, the IRG team has also now fabricated ultra long gallium nanowires within the pores of optical fibers (as part of their redirection).

The Center has continued to make major advances in nanostructures grown in mesostructured optical fibers (MOFs) and planar metallodielectrics. The IRG team has successfully fabricated single-mode amorphous silicon optical fiber cores and demonstrated all-optical signal processing. Tapered fibers filled with arrays of Ge nanowires have been developed into a near-field high resolution IR imager. Crystalline compound ZnSe in-fiber systems are being doped for use in high power tunable IR fiber lasers. p/n and metal-semiconductor junctions inside fibers are also being further developed. In the planar systems, the team has designed and fabricated dispersion engineered metamaterials for broad-band performance. Metal-free all-dielectric zero index and perfect magnetic conductors have also been achieved. Target structures for future optically thick nanostructures have been developed for the future redirection of this IRG.

**Broader Impact.** The Center continues to serve as a hub for connecting students, post-docs, and faculty at Penn State to a wide range of outreach educational and outreach activities. The Center’s outreach targets the *audience of many* by engaging the complementary skills of partner institutions, such as the museum shows in partnership with the Franklin Institute. These museum shows at the Franklin and 24 partner science museums were estimated to reach over 110,000 participants in 2011. The Center’s outreach also targets the *audience of one*, through hands-on research experiences, summer camps, workshops, and local events that benefit both participants and student mentors from the Center. In 2011, the fourth museum kit/show on renewable energy was distributed to partner science museums and the initial design of the fifth kit/show was initiated. Two successful summer camps were delivered in 2011, one targeting a young demographic and another aimed at high-school students being groomed for future leadership roles (*Science Leadership Camp*). The latter camp included a very successful evening mixer between the campers and MRSEC scientists at all levels. The Center continues to work energetically to increase the participation of women and underrepresented minorities at all levels. At the K-12 levels, diversity-focused activities included the science leadership camp and guided inquiry summer laboratory experiences for high school students from disadvantaged schools through the Upward Bound program. The Center’s REU program continues to be strongly diversity-focused, leveraging partnerships with minority-serving institutions in Puerto Rico, Texas, and Louisiana.
2. List of Center Participants

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<thead>
<tr>
<th>Bioengineering</th>
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<tbody>
<tr>
<td>Peter Butler</td>
<td>Center Affiliate Seed yes</td>
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<tr>
<td>Chemical Engineering</td>
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<tr>
<td>Kyle Bishop</td>
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<tr>
<td>Ali Borhan</td>
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<td>Enrique Gomez</td>
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<td>Darrell Velegol</td>
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<td>Chemistry</td>
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<td>David Allara</td>
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<td>John Asbury</td>
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<td>John Badding</td>
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<tr>
<td>Jacqueline Bortiatynski</td>
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<tr>
<td>Lasse Jensen</td>
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<tr>
<td>Thomas Mallouk</td>
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<td>Scott Phillips</td>
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<td>Ayusman Sen</td>
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<td>Raymond Schaal</td>
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<td>Electrical Engineering</td>
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<td>Suman Datta</td>
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<td>Thomas Jackson</td>
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<td>I. C. Khoo</td>
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<td>Zhiwen Liu</td>
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<td>Theresa Mayer</td>
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<td>Tony Jun Huang</td>
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### Materials Science and Engineering

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<tr>
<td>Long-Qing Chen</td>
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<tr>
<td>Venkatraman Gopalan</td>
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<tr>
<td>Michael Hickner</td>
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<td>Suzanne Mohney</td>
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<td>Susan Trolier-McKinstry</td>
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<td>Joan Redwing</td>
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### Physics

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<td>Moses Chan</td>
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<tr>
<td>Vincent Crespi</td>
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<td>Jainendra Jain</td>
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<td>Ronald Redwing</td>
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<td>Nitin Samarth</td>
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<tr>
<td>Peter Schiffer</td>
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<tr>
<td>Jorge Sofo</td>
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<tr>
<td>Jun Zhu</td>
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Jayatri Das (Education) Franklin Institute (Received Center Support in a subcontract)
Steven Snyder (Education) Franklin Institute (Received Center Support in a subcontract)
Craig Fennie (IRG 1) Cornell University (Received Center Support in a subcontract)
Darrell Schlom (IRG 1) Cornell University (Received Center Support as a co-advisor of 2 students working in IRG 1 with Long-Qing Chen)
Xiaoqing Pan (IRG 1) University of Michigan (Received Center Support in a subcontract)
Karin Rabe (IRG 1) Rutgers University (Received Center Support in a subcontract)
Ramesh Ramamoorthy (IRG 1) UC Berkeley (Received Center Support in a subcontract)
Kevin Kelly (IRG 2) Rice University (Received Center Support in a subcontract)
James Tour (IRG 2) Rice University (Received Center Support in a subcontract)
Paul Weiss (IRG 2) UC Los Angeles (Received Center Support in a subcontract)
3. List of Center Collaborators

<table>
<thead>
<tr>
<th>Collaborator</th>
<th>Institution</th>
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<th>Field of Expertise</th>
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<th>Shared Facilities User</th>
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<tr>
<td>Martin Holt</td>
<td>Argonne Photon Source</td>
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<td>Nanoscale Xray imaging</td>
<td>IRG 1</td>
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<tr>
<td>Jiamian Hu</td>
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<td>Phase Field Modeling</td>
<td>IRG 1</td>
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<tr>
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<td>Piezoelectric Force Microscopy</td>
<td>IRG 1</td>
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<td>Anna Morozovska</td>
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<td><a href="mailto:Anna.n.morozovska@gmail.com">Anna.n.morozovska@gmail.com</a></td>
<td>Theory</td>
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<tr>
<td>Simon Phillpot</td>
<td>University of Florida Gainesville</td>
<td><a href="mailto:sphil@mse.ufl.edu">sphil@mse.ufl.edu</a></td>
<td>First Principles theory</td>
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<tr>
<td>Eric Clément</td>
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<td><a href="mailto:Eric.clement@upmc.fr">Eric.clement@upmc.fr</a></td>
<td>Physics of colloidal particles</td>
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<tr>
<td>Misael Diaz</td>
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<td>Modeling, Bacterial</td>
<td>IRG 2</td>
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<td>Modeling</td>
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<tr>
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<td><a href="mailto:Leonhard.grill@physik.fu-berlin.de">Leonhard.grill@physik.fu-berlin.de</a></td>
<td>Nanocar Analysis</td>
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<tr>
<td>Mauricio Hoyos</td>
<td>ESPCI (Paris Tech)</td>
<td><a href="mailto:hoyos@pmmh.espci.fr">hoyos@pmmh.espci.fr</a></td>
<td>Physics of colloidal particles</td>
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<tr>
<td>Jianzhuang Jiang</td>
<td>University of Science and Technology Beijing</td>
<td><a href="mailto:jianzhuang@ustb.edu.cn">jianzhuang@ustb.edu.cn</a></td>
<td>Synthesis</td>
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<tr>
<td>Anotoly Kolomeisky</td>
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<td><a href="mailto:tolya@rice.edu">tolya@rice.edu</a></td>
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<td>Stephan Link</td>
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<td><a href="mailto:slink@rice.edu">slink@rice.edu</a></td>
<td>Single molecule fluorescence spectroscopy</td>
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<td>Angel Marti</td>
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<td><a href="mailto:amarti@rice.edu">amarti@rice.edu</a></td>
<td>Solution spectroscopy</td>
<td>IRG 2</td>
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<tr>
<td>Mogens Brondsted Nielsen</td>
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<td><a href="mailto:mbn@kiku.dk">mbn@kiku.dk</a></td>
<td>Molecular Engineering</td>
<td>IRG 2</td>
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<td>Anne Rousselet</td>
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<td>Physics of colloidal particles</td>
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<td>Gemma Solomon</td>
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<td>Nanoscience</td>
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<td>Fraser Stoddart</td>
<td>Northwestern University</td>
<td><a href="mailto:stoddart@northwestern.edu">stoddart@northwestern.edu</a></td>
<td>Molecular Motors and Nanomaterial synthesis</td>
<td>IRG 2</td>
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<tr>
<td>Yang Wang</td>
<td>UCLA</td>
<td><a href="mailto:yangy@ucla.edu">yangy@ucla.edu</a></td>
<td>Materials Science and Engineering</td>
<td>IRG 2</td>
<td>Yes</td>
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<tr>
<td>Lin He</td>
<td>Beijing Normal University</td>
<td><a href="mailto:helin@bnu.edu.cn">helin@bnu.edu.cn</a></td>
<td>Magnetic and Electronic Properties of Low Dimensional Systems</td>
<td>IRG 3</td>
<td>Yes</td>
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<td>Mingliang Tian</td>
<td>Chinese Academy of Science</td>
<td><a href="mailto:tianml@hmfl.ac.cn">tianml@hmfl.ac.cn</a></td>
<td>Superconductivity and Magnetism</td>
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<td>Jian Wang</td>
<td>Peking University</td>
<td><a href="mailto:Jianwangphysics@pku.edu.cn">Jianwangphysics@pku.edu.cn</a></td>
<td>Superconductivity, Magnetism and Topological Insulator</td>
<td>IRG 3</td>
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<tr>
<td>Noel Healy</td>
<td>University of Southampton</td>
<td><a href="mailto:nvh@orc.soton.ac.uk">nvh@orc.soton.ac.uk</a></td>
<td>Fiber materials and devices</td>
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<td>Priyanth Mehta</td>
<td>University of Southampton</td>
<td><a href="mailto:Pm4g09@orc.soton.ac.uk">Pm4g09@orc.soton.ac.uk</a></td>
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<tr>
<td>Mario Pantoja</td>
<td>University of Granada, Spain</td>
<td><a href="mailto:Mario@ugr.es">Mario@ugr.es</a></td>
<td>Computational Electromagnetics</td>
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<td>Anna Peacock</td>
<td>University of Southampton</td>
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<td>Spin injection and Spin Transport in Semiconductors</td>
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4. Strategic Plan

Development of Center Vision and Mission: Nanoscale science is a rich field that is transforming materials science, not only by providing materials with enhanced properties for traditional applications but also by providing access to wholly new, transformational physical phenomena. Over the next decade, nano-materials are expected to play an increasingly important role in energy conversion, electronics, biology, environmental technology and other fields. In large measure the success of these applications depends on innovation in materials discovery and assembly, and especially on understanding of new physics that is unique to the nanoscale. Recognizing the importance of the connection between emerging science and societal benefit, the mission of the Center is to design and discover materials with fundamentally new physical properties and functions, focusing especially on phenomena that are unique to nanoscale dimensions. Success in this effort requires the participation of multi-disciplinary teams that combine expertise in materials synthesis, fabrication, theory and computation, physical property measurements and device engineering. Projects in the Center are expected to be at the forefront of their field scientifically, to be intrinsically interdisciplinary and in appropriate cases to transition to practical technology. Considering the scale of the Center, the projects should assume greater risk and ambition than a typical single-investigator effort. Renewal of the Center’s scientific focus is driven by new discoveries in the interdisciplinary research groups, and by a robust seed program that draws on talent from a large pool of materials researchers at Penn State and collaborating institutions. Periodic internal review of all programs is an important factor in maintaining the high quality and productivity of Center research. Center research is integrated with educational and industrial outreach that is designed to engage all its members and leverages the expertise and distribution networks of several partner organizations: these efforts are seen as valuable not only for the recipients (the public, students, industry) but also for the participants, as career development experience in communicating and translating research towards larger societal needs. The Center supports the career development of young scientists and those from under-represented groups through its seed program, internships, coordination with departmental admissions committees, research experiences, participation in the materials facilities network, and outreach activities, as described in the Diversity Strategic Plan. This management philosophy and strategic plan for the Center has been developed jointly by the members of the IRGs, who meet weekly for seminars and informal discussions, by the past and present Center directors, and by the Executive Committee. It is expected that the future vision for the Center will continue to evolve with bottom-up input from its creative and energetic membership.

Research Goals: Transformed by the injection of new ideas and new participants, the topical emphasis of the IRGs has changed substantially since the Center’s establishment. The core research goals of the Center in hard and soft materials were re-defined by the four IRGs in the competitive renewal process of 2008. In initiating new projects and evaluating continuing ones, the Center responds to new scientific opportunities and societal needs by exploiting synergistic collaborations across fields. The following provides a picture of the Center’s current activities and research goals for the next two years:

IRG1 will focus on strain tuning and (in a new initiative) layer tuning and resulting new phenomena in complex oxides in which two or more ferroic (ferroelectric, ferroelastic, magnetic) order parameters exist within a single material. The intricate coupling between spin-charge-and-lattice degrees of freedom are expected to give rise to a rich spectrum of new phenomena and
cross-coupled properties with fundamental scientific merits on their own, as well as potential applications in highly tunable electronic and optical properties, and electrical control of magnetism. Predictive theory plays a crucial role in these studies.

**IRG2** will focus its efforts onto catalytic nano/microscale motors that employ catalytically driven ion flow, hydrolysis, and (in a new initiative) acoustic energy will be designed, fabricated, and modeled, inspired by the dynamic interplay of nanomachines that comprise living systems. This research will advance the fundamental understanding of nanomotor design to enable applications in the dynamical organization of nanomaterials and nanosystems, separations, sensing, actuation and biomedicine. Particular focus will be placed on collective interactions between motors, and the extension of motor functionality by incorporation of internal state variables.

**IRG3** will explore new phenomena related to charge and spin transport in quasi-1D nanostructures, using single-crystal nanowires grown by electrochemical, CVD methods and (in a new initiative, fiber deposition at extreme aspect ratios a novel multiwire configurations) and coupling theoretical modeling to low-temperature transport measurements. This effort is motivated by fundamental questions that may also have technological applications in superconductivity and semiconductor nanowire electronics.

**IRG4** seeks to design and fabricate in-fiber and planar nanostructured devices that manipulate and channel electromagnetic (E-M) radiation across the spectrum, with a new focus on the creation of optically thick structures, “thick films,” through transformative new techniques of directed assembly and high-pressure deposition in confined planar geometries. The goals of the work are to access new physical regimes and enable new technologies by directing the spatial organization and integration of metals, semiconductors, and dielectrics on sub-wavelength length scales. Feed-forward computational methods are a key component of these material and device designs.

The **seed grant program** will continue to be an important avenue for promoting new research ideas, particularly high-risk projects proposed by both early-career and established faculty, as described earlier. A strong matching commitment from Penn State allows the Center to support several seed projects in each annual competition. Historically, the seed program has been an important engine of innovation in the Center; for example, it led to the establishment of a new IRG (now IRG1) in the latest renewal. In 2011, a major re-envisioning of each IRG was implemented via a special Seed program that drew resources from the IRGs existing budgets and re-allocated them through the vehicle of IRG redirection seeds, in addition to an open competition for a new seed intended to spark a competitive new IRG.

**Metrics:** The Center’s metrics for success include the number of collaborative publications, particularly those in high-profile journals and with multi-point collaboration, the degrees, training, outcomes and further career development of a diverse body of participants, numbers of patents, development of industrial and international collaborations, industrial co-sponsorship of research, and transfer of technology developed in the Center.

**Educational and Diversity Goals:** The Center maximizes its educational impact by coupling the expertise and enthusiasm of all of its members with our partners' expertise in reaching large audiences. The **Science-U** summer camps, offered across grades 3–11, will continue to develop new content on topics that resonate with the public (Mythbusters, Crime Scene Investigators, Harry Potter, etc.). In partnership with The Franklin Institute (TFI), new museum shows will be
created for distribution to a national network of science museums, reaching an audience of hundreds of thousands. We are recruiting at the high school level students both locally and from underrepresented groups in the Philadelphia area for a Science Leadership summer camp. A broad range of high schools and middle schools are being reached through teacher training workshops and research experiences, and a diverse group of students are mentored in the REU program, recruited through partnerships with minority-serving institutions. All major outreach programs are regularly assessed for efficacy and impact. Center outreach activities will continue to be integrated into the Center’s ongoing research activities through outreach showcases embedded into the MRSEC seminar series, participation across all levels in education and outreach activities, and the involvement of outreach staff in regular IRG research meetings and activities.

The Center recruits students and postdocs from under-represented groups through ongoing collaborations with partner institutions in Puerto Rico and Texas, through the MRSEC facilities network, and by cultivating faculty contacts with minority-serving institutions as possible seeds of future PREM proposals. The goal here is to increase the representation of women and minorities at all levels in the Center and substantially exceed the level of their representation at Penn State as a whole. By coordinating with diversity-focused recruiting efforts across the campus through our Diversity Committee, the Center serves as a model and an agent for positive change in developing a diverse, interdisciplinary scientific workforce.
IRG1: Strain-Enabled Multiferroics

IRG Faculty and Seed Faculty: V. Gopalan (IRG leader), L.Q. Chen, P.E. Schiffer, R. Engel-Herbert, S. Trolier-McKinstry (all Penn State), X.X. Xi (Temple), D.G. Schlom (Cornell), K.M. Rabe (Rutgers), R. Ramesh (UC Berkeley), X.Q. Pan (University of Michigan), C. Fennie (Cornell).

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Current: Charles Brooks (Penn State), Benjamin Winchester (Penn State), Che-Hui (Kevin) Lee (Penn State), Yijia Gu (Penn State), Alexander Melville (Cornell), Turan Birol (Postdoc, Cornell), Ryan Haislmaier (Penn State), Jessica Leung (Penn State), Arnab SenGupta (Penn State), Raegan Johnson (Penn State), L. Palova (Rutgers), Craig Eaton (Penn State), Anil Kumar (Rutgers), Guangsha Shi (Michigan), James Clarkson (Berkeley), Qibin Zhou (Rutgers), C. Eaton (Penn State), Hena Das (Postdoc, Cornell).

Overall Goal: This IRG broadly focuses on strain tuning and the resulting new phenomena in multiferroic materials in which two or more ferroic (ferroelectric, ferroelastic, magnetic) order parameters exist within a single material. The intricate coupling between spin-charge-and-lattice degrees of freedom gives rise to a rich spectrum of new phenomena and cross-coupled properties with fundamental scientific merits on their own, as well as potential applications in highly tunable electronic and optical properties, and electrical control of magnetism. The IRG in particular focuses on complex oxides, and the strain tuning is imparted in thin films of high crystalline perfection and precisely controlled strain state by appropriate choice of substrates and growth conditions through conventional and laser-based molecular beam epitaxy methods. The team’s expertise spans first principles and phase-field modeling predictions of new materials and phenomena, synthesis, structural electrical, magnetic, and optical characterization, and prototype device demonstrations.


RESEARCH HIGHLIGHTS AND PLANS:

• A paraelectric antiferromagnet in bulk form such as EuTiO$_3$, when biaxially strained in thin film form becomes a strong ferroelectric ferromagnet (Nature, 2010$^4$, 2011$^5$).


Some of the above highlights are described below.

Hidden Symmetries in Octahedral Rotations (Nature Materials, 2011)$^2$: The structure of materials is described by a combination of rotations, rotation-inversions and translational symmetries. By recognizing the reversal of static structural rotations between clockwise and counterclockwise directions as a distinct symmetry operation, $I_\Phi$, (see Figure 1) Gopalan and Litvin$^1$ have shown that there are many more structural symmetries than are currently recognized in right- or left-handed handed helices, spirals, and in antidistorted structures composed equally of rotations of both handedness. For example, though a helix or spiral cannot possess conventional mirror or inversion symmetries, they can possess them in combination with the rotation reversal symmetry. Similarly, many antidistorted perovskites possess twice the number of symmetry elements as conventionally identified. These new symmetries, referred to as “roto” symmetries, predict new forms for roto properties that relate to static rotations, such as rotoelectricity, piezorotation, and rotomagnetism.

Future Plans: These symmetry insights enable a symmetry-based search for new phenomena, such as multiferroicity involving a coupling of spins, electric polarization and static rotations (Figure 1). One of the first goals is to experimentally test for the presence of this new symmetry in complex oxides.

![Figure 1](image-url)
Gopalan has recently identified tilt structures in simple perovskites given by the general Glazer notation, \(a^b_c\) and its variants to show new forms for tensor properties such as elasticity and dielectric constant. These predictions are being tested using first principles and phase-field modeling. Fennie has predicted \(\text{Ca}_3\text{Mn}_2\text{O}_7\) to couple polarization and magnetism through octahedral rotations. These will be experimentally studied. Spaldin group has predicted piezorotation in strained \(\text{LaAlO}_3\) from first principles. These films have been synthesized by Schlom group, and Trolier-McKinstry and Gopalan groups will visit Argonne for structural characterization in 2012.

**Highly Tunable Polar States, Bloch and Néel-type walls, and Dipole Spring Ferroelectrics:** Metastable phases are intermediate bridging phases that may not exist in a material under thermodynamic equilibrium, but are stabilized by inhomogeneous composition, stress, strain, and fields. One of the well-known examples is the monoclinic phase in \(\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3\) (PZT), and related solid solutions, occurring in the so-called compositional “morphotropic” phase boundary (MPB) and results in up to two orders of magnitude increase in piezoelectric response.

How can such phases be induced in material systems that do not possess a compositional MPB? Using phase-field theory and experiments, Gopalan and Chen have recently discovered (see Figure 2, also manuscript in preparation) that even single crystals of simple lead-free perovskites such as \(\text{BaTiO}_3\) and \(\text{KNbO}_3\) exhibit metastable monoclinic phases stabilized by local elastic and electric field gradients arising from twinned domain wall structures. We believe that such highly tunable states are responsible for the (previously unexplained) up to two orders of magnitude enhancement in piezoelectric coefficients observed in the presence of domain and twin walls. One of the most effective means of creating bulk monoclinic metastable phases is in layered structures. Figure 2 shows phase-field simulation by Chen group in an artificially layered, and strained \(\text{BaTiO}_3/\text{SrTiO}_3\) heterostructure. There are several surprising and striking aspects of this prediction: (1) The heterostructure is monoclinic, while neither of the constituent compounds is monoclinic. (2) Unusual vortex-type domain walls appear, that are Bloch-like and Néel-like in the directions perpendicular and parallel to the substrate. Note that textbook definition of ferroelectric walls is strictly considered to be Ising like. (3) The switching dynamics of this heterostructure exhibits unusual pinched hysteresis loops. A large section of this loop is reversible, leading to large tunability, hence called dipole springs. **Future Plans:** We propose to explore a range of layered structures to create such highly tunable polar phases with

![Figure 2](image-url)
unusual domain walls and highly tunable monoclinic phases.

Revealing Ferroelectric Switching Dynamics with Atomic Resolution:
Ferroelectric materials are characterized by a spontaneous polarization, which can be reoriented with an applied electric field. The switching between polarized domains is mediated by nanoscale defects. Understanding the role of defects in ferroelectric switching is critical for practical applications such as non-volatile memories. This is especially the case for ferroelectric nanostructures and thin films in which the entire switching volume is proximate to a defective surface. Pan, Chen, Schlom groups have demonstrated\textsuperscript{8,9} the nanoscale ferroelectric switching of a ferroelectric thin film under an applied electric field using \textit{in situ} transmission electron microscopy (Fig. 3). We found that the intrinsic electric fields formed at ferroelectric/electrode interfaces determine the nucleation sites and growth rates of ferroelectric domains and the orientation and mobility of domain walls, whereas dislocations exert a weak pinning force on domain wall motion. Future Plans: With aberration correction transmission electron microscopy, we plan to probe the internal structure and dynamics of ferroic walls, as well as oxygen octahedral rotations in thin films.

(Anti)Ferroelectricity and the Role of Dimensionality in Layered Ruddlesden-Popper Complex Oxides: (Anti)ferroelectric and antiferrodistortive states are cooperative phenomena involving the coherent motion of atomic distortion patterns extending over many unit cells. These ferroic states may be greatly influenced by introducing a perturbation with a characteristic length scale below (or near) that of the coherence length of the ferroic distortion. Layered structures allow a unique ability to tune the coherence length through layer dimensionality and strain. For example, Ruddlesden-Popper (RP) layered phases (Fig. 4), given by the general formulae $A_{n+1}B_nO_{3n+1}$, can be considered as alternating layers of perovskites ($ABO_3$) and rock salt (AO), given by the sequence, $n(ABO_3)/AO$. Recently, Birol and Fennie have predicted\textsuperscript{21} from first principles calculations an unusual polar state in the low $n$, Sr$_{n+1}$Ti$_n$O$_{3n+1}$, at small values of tensile strain, in which ferroelectricity is nearly degenerate with true antiferroelectricity, a relatively rare form of ferroic order. With increasing $n$ at a fixed value of epitaxial strain, a region of the phase diagram is reached where \textit{ferroelectricity and antiferroelectricity compete}. Beyond a critical $n > n_c$, an \textit{in-plane polarization} sets in within the perovskite layers. Future Plans: Preliminary results on strained Sr$_{n+1}$Ti$_n$O$_{3n+1}$ appear to confirm these predictions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{A contour map of the domain outline at each time step with the color corresponding to the domain wall velocity. Line profiles for the initial vertical velocity and lateral velocity versus time of the left domain wall are overlaid. In both cases, a pinning event is highlighted by a white arrow. scale bar, 50 nm. (Nat. Comm. 2011)$^9$
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Homologous Ruddlesden-Popper series of compounds Sr$_{n+1}$Ti$_n$O$_{3n+1}$.}
\end{figure}
indicates the importance of the dimensionality “n” in turning on and off the ferroelectric properties of the series. We propose to construct a simple microscopic model that allows us to understand how (anti)ferroelectricity emerges as the number of perovskite blocks $n$ increases. These insights could enable the RP structure to serve as a general template for a new class of ferroelectric and multiferroic materials with coupled properties.

**Hybrid Improper Multiferroicity through Coupled Octahedral Rotation Modes:**

The recent discovery of rotation-driven ferroelectricity in an artificially layered superlattice of PbTiO$_3$/SrTiO$_3$ by Bousquet et. al.\textsuperscript{52} exhibits a trilinear coupling, namely, $F=\gamma R_1 R_2$, comprised of two different rotation modes, $R_1$ and $R_2$, leading to a hybrid mode. In the last year, Benedek and Fennie\textsuperscript{53} have identified a naturally layered Ruddlesden-Popper system, Ca$_3$Ti$_2$O$_7$, in which such trilinearly coupled rotations induce ferroelectricity with a polarization as large as 20$\mu$C/cm$^2$. They have suggested the term hybrid improper ferroelectricity. Fennie and Rondinelli\textsuperscript{54} have recently developed a general design criterion for hybrid improper ferroelectricity by which otherwise centrosymmetric octahedral tilt patterns can give rise to ferroelectricity in layered (A,A')B$_2$O$_6$ perovskite structures.

Polar distortions typically mostly do not appreciably influence the interactions between spins, and hence not conducive to generating a strong polarization-magnetization coupling. Octahedral rotations solve this problem. The mechanism of hybrid improper multiferroicity provides lattice layering as an additional degree of freedom for controlling magnetization. Further, this approach supports electric polarizations in more diverse chemistries, including cations with strong magnetic interactions, open $d$- and $f$-shell configurations, which are incompatible with conventional ferroelectricity. Fennie and Benedek have also predicted\textsuperscript{53} the naturally occurring Ca$_3$Mn$_2$O$_7$, a Ruddlesden-Popper layered phase [Fig. 5], to possess such hybrid improper multiferroicity. They show that the transition from paraelectric to the ferroelectric state was driven not by a polar instability, but by two different octahedral rotation modes, with different symmetries, forming a hybrid mode. The direction of the polarization can be switched by switching either the $X_2^+$ mode, or the $X_3^-$ mode, but not both. By switching the $X_3^-$ mode, the direction of weak-ferromagnetization will also switch. Thus Ca$_3$Mn$_2$O$_7$ is a fully coupled multiferroic.

**Future Plans:** We propose to experimentally pursue these exciting theory predictions in layered perovskites. Ruddlesden-Popper phases like Ca$_3$Ti$_2$O$_7$ will be pursued. Layered (A,A')B$_2$O$_6$ perovskite structures will be pursued, in vastly different chemistries: gallates, aluminates, ruthenates, zirconates, and vanadate. Multilayers such as LaAlO$_3$/YAlO$_3$, LaAlO$_3$/BiAlO$_3$, YAlO$_3$/YGaO$_3$, LaGaO$_3$/YGaO$_3$, SrVO$_3$/CaVO$_3$, CaZrO$_3$/SrZrO$_3$ and others have been predicted by Rondinelli and Fennie to possess significantly large $\sim 10\mu$C/cm$^2$ polarization. These systems will be pursued. We have already synthesized Ca$_3$Mn$_2$O$_7$ by MBE, and are experimentally probing the multiferroic phenomena presently.

**Figure 5: Fully coupled ferroelectric, weak-ferromagnet:** Ca$_3$Mn$_2$O$_7$ structure (a) with Ca (blue) and O (red) shown. The (b) $X_2^+$, and (c) $X_3^-$ rotation modes.
REFERENCES


IRG2: Powered Motion on the Nanoscale

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Goals and Highlights: IRG2 aims to engineer autonomous motion of objects and fluids spanning from the nano to the microscale, to attack one of the grand challenges in science: How can we master and control energy and information on the nano and microscale to create new technologies with capabilities ultimately rivaling those of living things? This level of control requires intelligent systems that are driven far from equilibrium through the use of free energy. A functioning intelligent system requires (a) information and (b) an information processor that acts on the information. Information can take the form of chemical, acoustic, or optical fields, with autonomous motile objects or fluidic pumps responding to and modifying this information. The coupling between sensing and transport could enable new applications such as dynamic spatiotemporal dissemination of materials and analyte-triggered cargo delivery. We have demonstrated, for the first time, that abiotic nano/micro-objects can move autonomously by converting chemical, photochemical, and acoustic energy into mechanical force. With minimal information input in the form of chemical, acoustic or optical fields, these objects begin to display rich, emergent collective behavior. The Galilean inverse, analyte-triggered pumping, was also demonstrated using surface-anchored motors. Freed of the usual biological constraints, we now have the unprecedented opportunity to probe the limits of self-organization in these dynamic systems that operate far from equilibrium.

Recent Accomplishments:
Single-enzyme molecules, polymerization catalyst-bound microparticles, and microparticles undergoing depolymerization all show enhanced diffusive motion in the presence of the specific substrate. Further, this increase is attenuated upon the addition of an inhibitor. The fundamental mechanisms that generate motion remain unclear in many cases, especially at the single-molecule level. Hypotheses to explain the motion include chemical gradients arising from asymmetric production of reaction products (osmophoresis), and non-reciprocal conformational changes during substrate turnover. The work on single catalyst molecules will link the nano-scale molecular motors with micro-scale catalytic motors as we scale-up from single catalyst molecules (enzymes) to the same catalysts tethered to micro-scale objects.

In what is effectively the Galilean inverse of the process just described, pumping of fluids is possible using surface-anchored motors in the presence of the specific substrate. The entropy-driven depolymerization pumps consist of insoluble polymer films that depolymerize to release
soluble monomeric products when exposed to a specific analyte. The pumps are self-powered: Products formed as a result of the depolymerization reaction create a concentration gradient that pumps fluids (and particles) away from the bulk polymer. Since the depolymerization of a single polymer chain triggered by one analyte molecule leads to a large number of monomer products, there is considerable signal amplification. The pumps are capable of turning on in response to specific analytes and are tunable to respond to a variety of analytes, ranging from small molecules to enzymes. In the current year, these pumps have been extended to new fuels and new geometries.

Directed (stochastic) diffusive motion up a substrate gradient (i.e., chemotaxis) occurs, and is observed with various types of motors over a large length-scale, including single enzyme molecules and polymerization catalysts bound to microparticles. Based on random-walk particle simulations, the chemotactic behavior of the enzyme molecules may arise from an enhanced diffusion mechanism. The substrate concentration changes continuously as the enzyme diffuses along the gradient. Thus, at every point in space, the diffusion rate increases on moving up the gradient and decreases on moving down the gradient. A higher diffusion coefficient leads to a greater spreading of the enzyme molecules on the side of the higher substrate concentration. The powered component of the motion is crucial, since it enables the microscopic irreversibility necessary for inhomogeneous diffusion to favor non-uniform spatial distributions. The proposed mechanism is stochastic in nature and is different from biological chemotaxis, which requires temporal memory of the concentration gradient.

Emergent swarming and predator-prey behavior based on chemotaxis occurs for particles and enzyme molecules that produce self-generated ion gradients. Controlled formation of zones of attraction and exclusion, as well as spatio-temporal reversibility, can be achieved. The collective emergent behavior of micro/nanoscale active particles can be explained by a self-diffusiophoretic mechanism. Each active particle secretes chemicals (cations and anions) that serve as signals to other nearby particles. When the neighboring particles are close enough to sense the signal, the diffusiophoretic flow that is caused by the ion gradient pushes/pulls nearby particles away/towards the active particle, leading to different kinds of collective emergent behaviors. Under certain conditions, collective oscillations in their motion arise. The collective motions of these powered nanoparticles self-organize into clumped oscillators with significant spatiotemporal correlations between clumps. The system appears to be at the edge of a bistable regime, wherein one unstable cluster sets off neighbors, and neighbors then set off further neighbors in a resettable chain reaction. The theory of this fascinating collective nonlinear particle/chemical field system is under active investigation.

The powered rotary motors are also expected to exhibit dynamical chiral symmetry breaking. An individual motor, unpowered and embedded in an isotropic background solution, is achiral: the cylindrical symmetry of the underlying linear motor is broken only by “shutting down” the motor functionality on one side of the cylinder: The overall rotor retains reflection symmetry and therefore does not have right and left handed subpopulations. Only when these motors are placed above a substrate and powered is the chiral symmetry broken and clockwise/counterclockwise subpopulations created. The powered motion is necessary to stabilize this chirality over time, since it is defined in terms of how the inactive side orients relative to the substrate at the moment that powered motion initiates. For fixed motor performance (in terms of speed along the main axis), the persistence of a given chirality will be a function of the strength of the
structural/propulsive symmetry breaking. However, for a population of independent, non-interacting rotors, this functional dependence will be a crossover, not a phase transition.

A direct comparison of previously-discovered catalytically powered Au-Pt motors with flagellar bacteria show that the two are very similar in their momentum transfer to unpowered tracer particles at surfaces, despite the very different propulsion mechanisms. This similarity underlies some of the biomimetic collective behavior of the nanorod motors, and is also important in considering how to mimic other emergent properties of bacterial motors, such as the colonization of surfaces to form biofilms.

Motors on length scales from 1 to 100's of microns can be powered by ultrasound and exhibit speeds of up to hundreds of microns per second. These larger micromotors function in a Reynolds number regime where directional motion is possible with a reciprocating two-state motor. These swimmers are likely to find themselves widely useful in numerous applications ranging from microfluidics such as selective mixing, pumping, and load transportation to any specific site to non-invasive medical and surgical needs such as targeted drug delivery, brachytherapy, and ablation.

Working with collaborator Mauricio Hoyos (ESPCI, Paris Tech), we have found similar rapid axial movement (>200 micron/s) and striking collective behavior with 2 micron bimetallic rods using ultrasound in the MHz range. In this case, the movement is less well understood. The two dominant effects appear to be the localization of particles at acoustic nodes and the scattering of sound waves from the metal rods, which have high acoustic contrast with the surrounding fluid. The "tweezer" effect levitates the rods to a plane one half wavelength above the transducer and the acoustic scattering gives rise to two kinds of autonomous motion: Axial motion that depends on the shape asymmetry of the rods (rods move away from their concave ends), and rotational motion that creates vortices in the fluid, which in turn forces the rods into polar chains. In related work on a longer length scale, we have designed acoustically powered lithographically defined motors based on oscillations of trapped bubbles, as depicted in the figure at right.

As part of the plan to design efficient plasmon-enhanced molecular devices, novel experimental techniques to investigate the interactions of surface plasmons with functional molecules on metal surfaces have been developed and used to follow the photochemistry and photophysics of isolated single molecules (0D), one-dimensional (1D) linear chains, and two-dimensional (2D) clusters of photochromic assemblies By employing precisely controllable molecular assembly techniques, in conjunction with highly sensitive surface-enhanced Raman spectroscopy (SERS) and high-resolution custom-built scanning tunneling microscopes (STMs), we were able to tune and to study the dipole-dipole interactions between vertically aligned functional molecules. The efficiency of photoswitching decreases dramatically with...
increase in the conductivity of linker that spatially separates the functional moiety from the conductive substrate. Moreover, the molecular assembly plays a critical role in the photoswitching efficiency; 0D assemblies exhibit faster photoswitching than molecules assembled in a 1D chain format, presumably due to steric hindrance.
IRG 3: Electrons in confined geometry

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The major theme of this IRG is the physics of superconducting, metallic, magnetic and semiconducting nanowires in the one dimensional limit. We will summarize below the progress we have made during the past year on a number of ongoing projects. We will also report on a new collaboration with IRG 4 in the study of submicron diameter superconducting and metallic wires of macroscopic (~10cm) lengths.

Measuring the spin reorientation dynamics in a single semiconductor/ferromagnet core/shell nanowire: The incorporation of spin-related functionality into semiconductor nanostructures provides an exciting new route for nanospintronic devices. Nanodevices derived from MnAs/GaAs heterostructures present an interesting opportunity in this context because GaAs is an important semiconductor for optoelectronics, while MnAs is a ferromagnetic metal with a Curie temperature above room temperature (313-350 K, depending on the strain). In addition, MnAs is a fundamentally interesting ferromagnet because of the unique competing interplay between the magnetocrystalline anisotropy and the shape anisotropy. We have demonstrated heteroepitaxial growth of GaAs/MnAs core/shell nanowires, thus creating a novel arena for studying magnetization dynamics in restricted nanoscale geometries. Probing the magnetization in such individual nanowires is a challenge for conventional magnetometry techniques. Instead, we used magnetoresistance measurements of single nanowire devices in conjunction with state-of-the-art micromagnetic simulations to gain insights into the magnetization reorientation process of core/shell GaAs/MnAs nanowires. The methodology we developed for probing the magnetization dynamics is also applicable to other ferromagnetic nanowires of
contemporary interest in spintronics. An initial paper describing the synthesis and characterization of these nanostructures was published in Applied Physics Letters. A new manuscript describing the correlation between magnetoresistance and magnetization reorientation in single nanowire devices has been accepted for publication also in *Applied Physics Letters*.

**Long Range Proximity Effect in Ferromagnetic Nanowires:** Due to conflicting spin order between conventional singlet superconductors and ferromagnets, the proximity effect in a ferromagnet is supposed to be limited to ~ 1nm. In 2010 we reported the unexpected result that when Co and Ni crystalline nanowires are contacted with superconducting W electrodes fabricated by the focused ion beam (FIB) procedure, a long range proximity effect ~ 600 nm was found. Recently we have replicated the effect in e-beam evaporated granular Co wire. The wire is also contacted by W electrodes by means of FIB. Theoretical studies on our results narrowed down the origin of the long range proximity effect in the ferromagnetic wires to (1) a metallic oxide layer around the Co or Ni wires, (2) weak damping of Josephson singlet supercurrent between the two superconducting electrodes and (3) triplet superconductivity.

We carried out measurements on crystalline Co nanowires with 4 normal Pt electrodes and a superconducting W strip between the two Pt voltage probes (inset Figure 2). Since the distance between the two voltage leads is about 5µm, a resistance drop of 30% from the normal state value at 1.9K indicates the spatial range of the proximity effect in this configuration remains of the same order as that seen before with four superconducting electrodes. This shows that the proximity effect cannot be caused by weak damping of Josephson singlet supercurrent between two superconducting reservoirs. Since Co and Ni oxide are insulating, this result supports the idea that the proximity induced superconductivity in the Co wire is indeed triplet in nature. Under a parallel field, two sets of magnetoresistance oscillations are seen (Figure 2). The oscillations with the larger period of ~ 1T appear to correspond to flux tubes passing through the nanowire. In the fluxoid quantization equation, \( BA = \phi_0 \) where B is the applied field, A is the area of the nanowire and \( \phi_0 \) is a flux quantum yields a wire radius of 25 nm. The actual wire radius is 35 nm, but if we take into account the presence of an oxidation layer, the two numbers are very close.

If the proximity effect induced superconductivity in the Co wire is triplet while the electrodes are standard BCS superconductors, it should be straightforward to fabricate simple devices to look for interference effects between the singlet and triplet supercurrents under a magnetic field. Such an experiment is in progress. To date only FIB fabricated W electrodes were used in these studies. It was pointed out that a spin disordered interface between the ferromagnetic film (or wire) and the (conventional singlet) superconducting electrode is necessary to ‘generate’ triplet superconductivity in the wire. It is possible that this interface is formed during the FIB process. We have initiated experiments to replace the FIB W electrodes with e-beam evaporated superconducting electrodes such as Al and Sn to see if the phenomenon survives without the FIB W electrode.

**Bi-stability and Quantum Phase Slips in Anti-Proximity Effect Induced Resistive State:** A superconducting system can be described by a complex order parameter \( \psi = |\psi|e^{i\phi} \). When the system is in the ‘phase coherent’ superconducting state, the phase \( \phi \) has a well-defined value throughout the system. In a phase slip event, the magnitude of the superconducting parameter at a point goes to zero momentarily, thereby making the phase ill-defined. When the order parameter recovers, the phase takes
on a value different from the previous value by $2\pi$. These phase-slip events are detectable because they cause a finite voltage to appear across the nanowire in accordance with the Josephson relation $d(\Delta \phi)/dt = 2eV/\hbar$, where $\Delta \phi$ is the phase difference across the nanowire. Phase-slip events occurring due to thermal activation at temperatures close to $T_c$ are well understood and documented. It is believed that these events can also be caused by quantum tunneling at low temperatures. Although there have been many attempts to detect these theoretically predicted ‘quantum phase slips’ by resistance measurements on superconducting nanowires, the results are inconclusive. Several years ago, this IRG discovered a counterintuitive phenomenon called the antiproximity effect (APE) wherein a bulk superconducting electrode suppresses or weakens the superconductivity of a superconducting nanowire. The phenomenon was found in crystalline, 40 nm diameter Zn nanowire arrays and later confirmed in granular Zn nanowires and crystalline and granular AlNW. Fu, Seidel, Clarke and Lee (PRL 96, 157005 (2006)) proposed that the resistive state of the Zn wires (when the electrodes are superconducting) is the consequence of quantum phase slips in the wires. Normal electrodes, on the other hand provide a dissipative environment which stabilizes the phase of the order parameter, preventing phase slip from disrupting superconductivity in the Zn wires.

![Figure 3](image.png)

Figure 3: (a) Four probe $R$ vs. $T$ measurements at different fields for a granular aluminum nanowire contacted with bulk aluminum electrodes. The loss of superconductivity of the nanowire at low temperatures where the electrodes are superconducting can be clearly seen. Each data point on this plot is an average of 50 resistance measurements. The inset shows a scanning electron micrograph of the sample. (b) The $R$ vs. $T$ at 300 Oe measured without the 50 point averaging. Each point now represents a single measurement. Below 0.35 K and between 0.7 and 0.84 K, the resistance registers two discrete values: zero resistance and the normal state. The transition between these states is caused by phase slips.

Figure 3(a) shows the resistance ($R$) vs. temperature ($T$) of a device consisting of an AlNW connected to four electrodes. The AlNW and the Al electrodes were fabricated by e-beam during the same evaporation step. The thickness of the device is 50 nm and the AlNW is 130 nm wide and 5 µm long. The electrodes are 1 µm wide. Measurements were made with an excitation current of 2.5 µA. Both the critical temperature ($T_c$) and critical field ($H_c$)of the electrodes are lower than that of the AlNW(0.7 vs. 0.9K for $T_c$ at zero field and ~380 vs. ~700 Oe for $H_c$ at 0.1K when measured with an excitation current of 2.5µA). If we follow $R$ as a function of $T$ at 300 Oe in Figure 3(a) as an example, we see that the wire begins to go superconducting when it is cooled below 0.8K. The resistance drops with decreasing temperature and achieves zero resistance slightly below 0.7K. At this temperature the electrodes are still normal. The zero resistance state persists down to 0.35K. Below 0.35 K, the resistance begins to increase with decreasing temperature saturating at half the normal state value near 0.1K, exhibiting APE behavior. The data shown in Figure 3(a) is obtained by averaging 50 resistance measurements at each field and temperature. To understand better the resistive state, we measure the $R$ vs. $T$ without averaging. This is shown in (Figure 3(b)). Above 0.84K, $T_c$ of the nanowire, the entire device is normal and shows temperature independent normal state resistance. Below 0.35 K and between 0.7 and 0.84K, the resistance registers only two
values, the normal state value or zero resistance. The resistance assumes one of these two values each
time an excitation current is injected. (The normal state resistance shows a monotonic decrease from 0.84
to 0.7 K, concomitant with the appearance of zero resistance readings. This decrease is probably due to
the fact that the boundary region between the electrodes and the wire is becoming superconducting.) The
averaged resistance values shown in Fig 3(a) in these temperature ranges therefore represent the
probability of the two (resistance) states the wire is ‘residing’. When the system is between 0.35 and 0.7
K, the AlNW is firmly locked in the superconducting state. We think the most sensible explanation of the
two discrete resistance readings is that the AlNW is in a bi-stable state in this region of parameters. This
is the case because the excitation current is close to the critical current and the free energies of the normal
and superconducting states of the device are nearly identical. The initiation of a measurement (by
application of an excitation current) chooses stochastically one of the two (normal or zero) resistance
states. The application of an excitation current may sometimes trigger a phase slip, which turns the wire
normal. Close to the transition temperature, (between 0.7 and 0.84K), the phase slips are likely thermally
activated. Below 0.35K the phase slips are likely due to quantum tunneling. The observation of quantum
phase slips at low temperatures is consistent with the model proposed by Fu et. al. for the APE.
Specifically in the temperature range between 0.35 and 0.7K, the electrodes are normal, providing
dissipative environment in stabilizing the AlNW in the superconducting state. However, when the
electrodes are superconducting below 0.35K this stabilizing mechanism is no longer present, which leads
to quantum phase slips that drive the nanowire into the normal resistive state. These phase slip are results
of quantum tunneling since the temperature is well below 0.84K, the transition temperature of the AlNW.
Our transport measurements on individual nanowires without averaging show results that suggest that the
AlNW superconducting wires in the 1D limit can reside only in two possible states with either zero
resistance or normal state resistance. It also suggests that phase slips are responsible in bringing the wire
from the zero resistance state to the normal state. It is natural to speculate that this phenomenon exists
also in other superconducting wires and we are in the midst of re-directing a number of experiments to
determine the ‘universality’ of these results.

Synthesis and Transport Studies of Ultrathin Nanowires: We have been developing a novel material-

general protocol for the synthesis of structurally and chemically re-enforced sub-10nm diameter single
crystalline nanowires of metals. The aim is to enable the systematic measurement of transport properties
by overcoming some of the technical barriers associated with ultra-thin nanowires. This approach
involves the controlled deposition of a thin insulating oxide on the pore walls of anodic alumina
membranes using atomic layer deposition, followed by the electrochemical deposition of the material of
interest within the pores. The wires are then released from the membrane with the protective oxide intact.
Contacting of the nanowire material for four probe measurements is achieved via the gentle, calibrated
milling of the oxide and subsequent deposition of electrodes. Contacting may be done using Focused Ion
Beam (FIB) deposition,which allows for ion milling during the deposition of contacts, or by using a
lithographic lift-off procedure with sequential milling and evaporation within the same chamber without
breaking vacuum. Our target materials include superconductors (e.g. Sn and Zn), ferromagnets (e.g. Co
and Ni) and elements( e.g. Bi. Pd and Pt).All of these wires are expected to show novel behavior in the
ultra-thin regime. We have conducted a proof of concept study of the process from beginning to end on
large diameter wires. We have synthesized gold nanowires within a hafnium oxide shell by the combined
ALD/electrochemical deposition approach. We have released and successfully contacted these wires
using FIB and conducted 4 probe transport measurements down to 50 mK.

Transport and electron drag measurements of 1 D wires of macroscopic lengths: The Penn State
MRSEC, specifically IRG 4, has the unique capability ingrowwingsemiconductor and metallic wires of
submicron diameter and macroscopic length (~1m) by high pressure depositioninto near atomically
smooth pores drawn in optical fibers.Recently Gallium wire of 150 nm diameter and length of a 1 meter
long has been successfully grown. Attempts in growing indium and tin wires of even smaller diameter are
currently in progress.
This capability provides an unprecedented opportunity for the study of 1D physics. Our experiments on superconducting wires to date have highlighted the role of the electrodes in affecting the behavior of the wires. While these effects are fascinating, it is difficult to separate the intrinsic behavior of the wire due solely to 1D confinement. Very long high quality long nanowires (of cm instead of micron length scale) should resolve such issues. Another very interesting question has remained largely unaddressed so far is the role of quantum confinement on 1D superconductivity. The nanowires studied to date are in the 1D limit in the sense that their width is smaller than the phase coherence length, but the effect of confinement is otherwise negligible. Long nanowires will enable an investigation of a direct transition from an insulator into a superconductor in some regions of the phase diagram, where the wires are long enough that the normal state is insulating due to Anderson localization, but not so long that the superconductivity is also fully destroyed. An identification of this regime will open the possibility of studies analogous to those carried out for superconductor to insulator transitions in 2D films.

The fiber platform allows for fabrication of coupled parallel wires with either two spatially separated parallel wires or two coaxial wires. Furthermore, these wires can be contacted separately, and one can control the amount of direct charge tunneling between them. This will allow the study of drag effects where a current flowing in one wire is predicted to induce a current in the adjacent wire as a result of inter-wire momentum relaxation by Coulomb interaction (or van der Waals interaction). If the other wire has no current drawn from it, a voltage will be induced, allowing a measurement of the “drag resistance.” Drag resistance is a very sensitive probe of interactions. While drag in two parallel 2D layers has given rise to much more interesting physics, very few measurements have been performed in 1D. The ability to make long 1D metallic wires gives us an opportunity to make sensitive measurements, as the induced voltage is proportional to the length of the wires. We consider three different cases. First, suppose that both wires are in the normal metallic state. If we consider Fermi liquid behavior in each wire, as appropriate for relatively larger diameters, then the detailed dependence of the drag resistance on the separation between the wires can be calculated and it has been predicted that the drag current is in the same direction as the driving current. In the 1D limit, when the Luttinger liquid behavior is relevant, theory predicts that the drag effect is actually stronger, diverging at zero temperature (because of a locking between the two Luttinger liquids), and following a power law dependence on the temperature determined by the Luttinger liquid parameter; detailed predictions can be made for the dependence of drag on the separation. Indeed this may be one avenue for us to confirm the presence of Luttinger liquid behavior. Second, imagine that both wires are in the superconducting regime. It has been predicted that a supercurrent in a superconducting wire will also induce a supercurrent in a parallel, spatially separated superconducting wire. Such an effect has not yet been confirmed. The third case of interest is one normal wire and one superconducting wire; a theoretical treatment is possible but has not yet been performed.

Figure 4: 150 nm diameter gallium wire 1 meter long fabricated in fiber pore by pressurized infiltration

Figure 5: Schematic of adjacent patterned in fiber nanowires
confinement on 1D superconductivity. The nanowires studied to date are in the 1D limit in the sense that their width is smaller than the phase coherence length, but the effect of confinement is otherwise negligible. Long nanowires will enable an investigation of a direct transition from an insulator into a superconductor in some regions of the phase diagram, where the wires are long enough that the normal state is insulating due to Anderson localization, but not so long that the superconductivity is also fully destroyed. An identification of this regime will open the possibility of studies analogous to those carried out for superconductor to insulator transitions in 2D films.

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IRG 4: Electromagnetically Coupled Nanostructures

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This IRG has made significant progress in designing and fabricating in-fiber and planar nanostructured devices, which are being used to manipulate and channel electromagnetic (E-M) radiation across the spectrum. Semiconductors and metals have been integrated in the extreme-aspect ratio pores of microstructured optical fibers and new all-fiber optoelectronic and nanoscale imaging devices that exploit E-M coupling at dimensions down to the nanoscale and lengths up to meters are being developed. Genetically-inspired feed forward design methods are being used to create planar metallo- and all-dielectric nanostructures with user-defined E-M scattering. New passive and active (e.g., tunable) infrared and visible devices including wavelength-selective filters and mirrors, and entirely new materials with customized refractive indices including zero and negative index have also been realized.

In-Fiber Devices Via High Pressure Chemical-Fluid Deposition: The controlled hierarchical assembly of individual nanoscale elements such as quantum dots and nanowires into high-quality, precisely designed functional materials and devices provides a compelling challenge in nanoscience. IRG4 researchers use optical fiber templates consisting of precisely structured arrays of nano/micropores to organize metals, semiconductors, and molecules that can be electromagnetically coupled with each other and to exterior structures in many useful ways. Using high-pressure chemistry, we have previously shown how Si pin photodiodes that detect visible wavelengths can be fabricated in optical fiber pores. We have now developed the high-pressure materials chemistry to make Pt/n-Si Schottky junctions (Fig. 1) that have the advantage of detecting light in the infrared region of the spectrum with 3 GHz bandwidth. The "outside-in" nature of this template-based approach to annular junctions contrasts with the usual approach of depositing on the exterior of nanowires. Despite the inherently low quantum efficiency of Pt/n-Si junctions, the 0.6 mm length our device allows for strong photoresponse when light at wavelengths shorter than 1550 nm is waveguided in the n'-Si layer. The responsivity is 1.4 mA/W, comparable to that of NiSi/n-Si waveguide photodetectors made by conventional techniques. This work, recently published in Nature Photonics, attracted considerable attention in the popular and scientific press (e.g., Materials Research Society Bulletin, PCWorld, IEEE Spectrum etc.) because it represents a significant step towards new types of 1-D lasers, detectors, and modulators seamlessly integrated into and coupled within optical fibers.

The direct coupling of the light in a silica single mode optical fiber (SMF) core (typically ~8 μm in diameter) to on-chip waveguide semiconductors photodetectors, for example, is subject to significant impedance mismatch and poor modal overlap because of the large...
differences in refractive index and size between them. In contrast, patterning a junction into a single capillary hole in a silica fiber template (Fig. 2) enables novel electromagnetic coupling scheme in which light is seamlessly and efficiently coupled from the glass fiber core to unbound modes of the semiconductor device. The loss spectrum reveals the (desired) increase in loss due to absorption by the junction structure when fiber modes couple to it.

**Germanium Core Waveguides:** Infrared (IR) imaging with high resolution is of increasing importance in research areas such as chemical sensing, biomedical diagnosis, thermography, non-destructive testing and astronomy. Contemporary high-resolution infrared imaging tools are based either on solid immersion lenses (SIL) or near-field scanning techniques, or a combination of both. The SIL offers diffraction limited imaging over larger areas with high optical throughput, while near-field technique offers excellent resolution beyond the diffraction limit, but with low optical throughput and longer acquisition times. For far-field infrared imaging, flexible fiber-optic bundle endoscopes are a preferred technique for rapid imaging of specimens with restricted optical access in a minimally invasive manner. The incumbent technology for IR imaging between 2 to 10 μm wavelengths using coherent fiber-optic bundles is based on arrays of either hollow metallic or chalcogenide core waveguides. These imaging bundles operate over a broad wavelength range, but have been limited to modest pixel sizes of the order of 50-100 μm. Therefore, there is a need for low-loss, broadband imaging systems with high resolution at mid-IR wavelengths.

We have recently demonstrated an IR imaging system with at least 2 μm resolution based on semiconductor waveguides deposited in silica tapered optical fiber templates. Germanium and silica waveguides were used to demonstrate imaging at wavelengths of 10.64 μm and 1.55 μm respectively. The essential features of the imaging system such as isolation between adjacent pixels, magnification, optical throughput, and image transfer characteristics were modeled and characterized. Near-field scanning at 3.39 μm wavelength using a single tapered Ge core is also demonstrated with a sub-wavelength, sub-diffraction resolution of ~2 μm. These are first-of-their kind imaging devices demonstrated so far, with high resolution, throughput, and magnification.

**Extending Chemical-Fluid Deposition:** IRG4 has pioneered a high pressure deposition process to grow metals, semiconductors, and dielectrics in spatially...
confined MOF geometries. Through our research it has become clear that a very different set of rules for realizing well-developed structures applies when the mean free path for molecules is ~1 nm and the spatial dimensions of the reaction chamber are nanometers to microns. We are continuing to develop this deposition technique through a combination of modeling and experiment. For example, plasma enhanced deposition provides a route to materials such as diamond that have optical and mechanical properties that would be useful to exploit in a fiber geometry. We have realized well-controlled, stable plasmas excited by radio frequency biases inside the pores of optical fiber templates. We have also extended the range of high pressure confined deposition to planar geometries by employing closely spaced parallel plates instead of fiber pores as the reaction chambers. This has allowed us to deposit materials such as doped hydrogenated amorphous Si to make planar Si solar cells. The advantage of this approach includes its simplicity in not requiring a large area plasma, its very high space efficiency, and its ability to convert silane precursor to Si with 100% efficiency. In contrast, conventional deposition approaches waste more than 2/3 of the expensive and valuable silane precursor.

Optical Metamaterials: This year we made significant progress in studying ways to overcome limitations in the field of optical metamaterials, such as bandwidth, loss, field of view (FOV), bianisotropy, and characterization techniques. As part of this effort we explored dispersion engineering techniques and applied them for the first time at optical wavelengths to develop a broadband negative- zero- positive- index metamaterial (NZPIM) that uses multiple magnetic resonances to maintain a matched impedance and high transmission as the refractive index varies from negative unity, through zero, to positive unity (see Fig. 4). This metamaterial forms a high quality passband filter function over the 3μm to 3.5μm band, which we demonstrated experimentally. We further designed and simulated the response of a polarization independent, beam-steering prism based on this metamaterial that steers an incident beam from 0° to 24° as the wavelength changes across the pass band region. We expect that this dispersion engineering design technique will become a primary approach in the future for overcoming loss and bandwidth limitations in practical optical metamaterial-enabled devices.

In addition to tackling loss and bandwidth, we have also focused on improving the field-of-view (FOV) in metamaterials. To this end, we have successfully designed, fabricated, and tested optical electromagnetic bandgap (EBG) metamaterial coatings with near-perfect absorption. In Fig. 5, the measured reflectivity, shown for various incident angles, are below 10 dB in bands at both 3.3 μm and 3.9 μm over a wide FOV of up to ±50° from...
normal incidence. The structure, shown in two insets, is composed of a Au back plane, a thin, flexible polyimide insulating layer, and a two dimensional periodic array of Au stub-loaded H-shaped nanopatches. The structure is conformal and maintains its absorbing properties independent of the supporting material.

Perfect mirrors serve as critical components in optical systems. Conventional mirrors are primarily made of noble metals that give rise to an out-of-phase reflection. To miniaturize system size, in-phase reflection is preferred, which can be theoretically achieved by perfect magnetic conductors. Several efforts have been reported in the microwave range on the realization of artificial magnetic conductors, but very little has been reported at optical wavelengths. We have completed the design, fabrication, and characterization of a high-performance artificial perfect magnetic mirror at near-IR wavelengths (see Fig. 6). Dielectric resonator arrays are used because they provide low loss, facilitating a nanostructured mirror with near-unity reflectivity and a near-zero reflection phase. This new type of optical mirror not only extends the functional realm of metamaterials, but also can find a wide variety of applications in nano-scale photonic systems.

Previously, anisotropic effective medium parameter tensors have been used to describe the bulk properties of optical metamaterials at normal incidence. However, it has been demonstrated that the asymmetry of these metamaterial structures in the direction of wave propagation, caused by the tapered side walls and/or a supporting substrate, introduces additional bianisotropy. We experimentally verified the substrate-induced bianisotropy at optical wavelengths by measuring the scattering parameters for a fishnet metamaterial mounted on a substrate from both sides. The bianisotropic effective medium parameters were then extracted, showing a magnetoelectric coupling parameter with non-zero values at the resonances. The measured results agree well with theoretical predictions (Fig. 7), thus confirming the bianisotropy introduced by the substrate. This experimental demonstration of substrate-induced bianisotropy provides useful insight into both the characterization and control of these often overlooked properties of optical metamaterials.

**Aperiodic Arrays of Plasmonic Nanoparticles:** We have investigated the near-field enhancement properties of quasicrystalline aperiodic Au nanoparticle arrays. These arrays lack the translational symmetry present in traditional periodic arrays, but they possess higher orders of rotational symmetries not possible in periodic structures. Aperiodic tilings provide much larger local field enhancements compared to periodic structures, which is of interest in engineering surface-enhanced Raman scattering (SERS) substrates because Raman enhancement...
is proportional to the fourth power of the near-field enhancement. Due to their higher order rotational symmetry, field enhancements also show much less dependence on the polarization of the incident radiation. Fig. 8 shows the local fields for a Danzer aperiodic tiling of 80 nm diameter Au spheres illuminated with 550 nm light. This array has a 7-fold rotational symmetry and provides a maximum local field intensity of 13.6 V/m, which gives a 13-fold SERS enhancement over a periodic array with similar properties (max enhancement of ~7.24 V/m). We are exploring aperiodic tilings for broadband absorbers where the structures couple into hybrid modes with multiple periodicities. To support this effort, we are developing new global optimization strategies that can be used to effectively search for aperiodic structures with the highest absorption over the broadest possible bandwidth.

**Future Directions:** We will continue to develop our deposition chemistry to allow for new materials and structures with useful E-M properties. We are refining our methods to fabricate layered structures such that their thickness can be controlled with great precision. We have also developed methods to fabricate single crystals within fiber pores from carefully chosen chemical precursors. These single crystals will enable a new generation of waveguiding and junction based devices with properties superior to those possible with polycrystalline materials. By structuring with layers and single crystals in each template pore, a complex hierarchy can be realized. For example, coherent beam combining of laser light from an array of structures in a fiber template may then become possible. Layered semiconductor Bragg mirror structures that hold promise for ultra-high power lightguiding fibers and attosecond laser pulse generation through high harmonic effects are also being developed. The advantage of these structures over state-of-the-art fiber polymer-based Bragg mirrors is that they are refractory and insensitive to damage from laser radiation.

We are also exploring alternative electric-field assisted deterministic assembly methods to form heterogeneous nanostructures as building blocks for metamaterial and transformation optics (TO) devices. These techniques are being used to manipulate nanoparticles over large areas with fast response times, providing the potential to construct tunable, 3D, and/or anisotropic optical metamaterials. Nanoresonators with complex structures, (core-shell spheres, pyramids, or disks), respond to the non-uniform electric fields generated by external stimuli, and are driven from or attracted to predefined locations by the dielectrophoresis (DEP) force or electroosmosis to form a desired structure. Initial results showing closely packed 2D nanoparticle arrays as well as 3D vertically oriented nanoparticle chains are shown in Fig. 9. Efforts are underway to characterize the optical properties of these assembled structures. The use of electric field gradients and forces to deterministically assemble arrays of subwavelength resonators that are registered to predefined features on a substrate provides a unique opportunity to construct complex 3D optical structures that are not accessible using conventional top-down fabrication methods.
**Seed Program:** In the past year a new Seed project has been initiated in an open competition to potentially spark a new IRG looking forward to the renewal. The title of the Seed is “Defect Engineering of 2-D Sheets of Layered Materials.” Defects are usually seen as imperfections in materials that could significantly degrade their performance. However, at the nanoscale, defects can be exploited to generate novel, and useful materials and devices. Defects in layered systems not only include familiar lattice defects such as topological ring defects, doping functionalization sites, vacancies or edge defects, but also novel folding defects when 2D objects deform in the third dimension. In addition, these defects can be studied directly from the surface, unlike the embedded defects in traditional 3D materials. Intense research world-wide on isolated graphene sheets has revealed the promise of 2D (layered) systems in supporting novel defect-generated electronic, optical, chemical, magnetic and mechanical properties, but the true promise of these systems lies in extending these investigations to a broader spectrum of layered materials—metallic, semiconducting or dielectric-outside the semi-metallic graphene ghetto. Structural or topological defects in 2D systems can generate new electronic, chemical, magnetic and optical properties that are absent in the pristine materials, such as metallic conduction in putative insulating h-BN sheets. Furthermore, stacking of diverse 2D sheets could produce novel heterostructures that cannot be grown by traditional epitaxial methods. Therefore, experimental control of defect type and location in diverse atomically layered systems needs to be studied and understood. Although defects in 3-D crystals have been studied at the micro-scale, a systematic study of defects in 2-D layered systems (outside graphene) has not been carried out. Furthermore, these 2-D sheets of layered materials could yield 1-D nanoribbons and platelets whose edges are crucial in determining their physico-chemical properties. For example, the edges of single-layered BN (insulating in the bulk) could behave as a metal and emit electrons efficiently via a conducting edge and sulphur passivation could make BN nanoribbons metallic. An enormous number of opportunities await to tailor the physical and chemical properties of single atomic layers via defect engineering.

By using chemical vapor deposition, the Seed team has recently been able to synthesize BN sheets and WS$_2$ triangular sheets. Furthermore, members of the team have performed extensive first-principles calculation in more complexed layered layered systems such as graphene, ZnO, and MoS$_2$ nanoribbons. The calculations have explored the possibility of fine-tuning the electronic and magnetic properties of nanoribbons or faceted 2D clusters, by controlling their width, edge shape, and number of stacking layers. Doping, in addition to edge- and surface-functionalization of these layered materials and nanoribbons, are indeed crucial for controlling their physico-chemical properties, and could yield to the observation of new phenomena that could result in the development of emerging technologies.
6. Education and Human Resources

MRSEC outreach and education programs strive to engage both participants and presenters in an exciting exchange of information, enthusiasm, and curiosity about science, technology, research, applications, and problem solving. Targeted participants and presenters include audiences from all stages along the pipeline, with special efforts made to create opportunities for interactions and communications between these multiple and diverse audiences. In an effort to bring awareness of new knowledge, current research, and the importance of the interdisciplinary cooperation that is inherent within the MRSEC itself, the themes and topics chosen for outreach programs and demonstrations often focus upon materials science and nanotechnology. Favorite MRSEC museum kit demonstrations and Nanoscale Informal Science Education (NISE) Network activities were often featured. 2012 records indicate that programs directly sponsored or supported by MRSEC engaged over 4,500 participants.

Including and engaging the faculty, research associates, postdoctoral fellows, and graduate students is a top priority. Outreach and education programs are essential to professional development because they create and/or improve the following: communication skills; positive relationships with local community groups, schools, and educators; networking opportunities to form broader interdisciplinary connections both within and outside the Penn State research community; the discovery of new mentors; a culture that deeply values scientific literacy and education. Therefore, one of MRSEC’s stated goals is for all faculty, researchers, post-docs, and staff to volunteer at least 12 hours towards outreach projects per year. Through the many opportunities, programs, and events that MRSEC sponsors and supports throughout the year, as well as efforts that members pursue on their own initiative, a positive impact is made on both the participants and the presenters.

Educational professional development opportunities also exist within the MRSEC culture, as all MRSEC members are expected to attend and participate in the weekly Monday Seminar. Whether as a presenter or audience member, the experience of explaining and clarifying important concepts, being exposed to new questions and ideas, and collaborating with an array of interdisciplinary expertise, the Seminar provides a tangible and important forum for potential seeds of inspiration and shared excitement about the ongoing progress of current projects.

Museum Show Partnership with the Franklin Institute

The longstanding collaborative partnership between the MRSEC and The Franklin Institute (a science museum in Philadelphia) resulted in the final completion and distribution of the fourth museum show titled Hidden Power. This cart-based exhibit features 8 demonstration activities that focus upon the conversion of various sources of energy to create electricity (or vice versa): Sources of Power, Turbines, Solar Panels, Batteries, Thermoelectricity, Piezoelectricity, Light Bulb Efficiency, and Light Emitting Diodes. All demonstrations are designed to be a hands-on experience for the visitor. They begin with an attention grabbing macroscopic example of the concept and are followed by a physical model and explanation on the nano or atomic scale. In addition to

Moses Chan engages visiting undergraduates from Bloomsburg University during a lab tour.
contribute initial inspiration and ideas, feedback during the development process, and ongoing technical oversight for accuracy, MRSEC faculty and graduate students also assisted in writing Fact Sheets to accompany each demonstration. Each two-page Fact Sheet provides information beyond the scope of the demonstration itself, and highlights current related research occurring within the MRSEC and broader Penn State community.

At a time when finding sustainable energy sources and reducing energy waste are of vital importance to our society, the Hidden Power exhibit has been met with tremendous enthusiasm and interest. Additionally, MRSEC faculty and graduate students participated in the final training meeting with staff from the 16 recipient museums. The chosen recipient museums represent a broad and diverse array of geographical locations, socioeconomic and ethnic populations, and museum sizes. During the 2012 calendar year, these museums will engage their visitors with these 8 demonstrations and measure their impact upon visitors. Two versions of the kit reside at Penn State, and therefore these demonstrations will be used and featured extensively by MRSEC members during the many upcoming outreach events in 2012 as well.

The history of the Center’s partnership with The Franklin Institute (TFI) now claims four accomplishments: Materials Matter (2003); Nano-Bio: Zoom in on Life! (2005); Small Wonders (2008); Hidden Power (2011). However, MRSEC members have already started on the next (and fifth) exhibit. A brainstorming meeting during December 2011 resulted in the seeds of a newly chosen theme: Portable/Handheld Electronic Devices. This kit will be developed over the coming year, with the goal of distribution to recipient museums during the fall of 2013.

Public Outreach Events

During 2011, MRSEC both continued and expanded its involvement in multiple outreach events. For volunteer presenters, these events created a sense of enthusiasm, camaraderie, and inspiration. One graduate student said, “In the lab, you are often by yourself and there are many times when things don’t go right, day after day. This can sometimes get discouraging and make you feel like you’ve got nothing to offer. But when you get out there and talk to people, you realize that you actually do have a lot to share. Outreach reminds me that I have learned a lot and it provides me with the opportunity to share what I have learned with others. I can spread my enthusiasm for science.” Additionally, these events strengthened relationships with the multiple science outreach partners with whom the Center collaborates.

The following programs and events reached public audiences:

**Penn State THON’s Make a Science Wish:** MRSEC graduate students provided hands-on science activities for 24 family members of children dealing with childhood cancer during Penn State’s annual fundraiser for the Four-Diamonds Fund, the largest philanthropy of its kind in the country;

**Exploration Day:** The Center staffed 18 volunteers to do eight engaging materials science activities at this popular annual local event that exposes many young families and community members of all ages to the many STEM groups that exist locally (~2000 attended the event);  

**Pennsylvania Junior Academy of the Sciences:** MRSEC members were judges at an annual state science competition where more than 3000 high school students from the state of Pennsylvania presented their science projects, answered questions, and were judged for prizes;
The Philadelphia Science Festival: MRSEC assisted Science-U staff and Science Lion Pride undergraduate students at a new (occurring for the first time in 2011) annual two-week event funded through NSF (Grant No. 0840333) which includes an exciting one day outdoor festival of science educational activities, demonstrations, information, etc.; Despite miserable weather and an early closing, more than 325 children (preK-12, not including parents, etc.) engaged in the science activity at the booth (approximately 10,000 attended the city event);

Central Pennsylvania Festival of the Arts - Kids Day: MRSEC graduate students, faculty, and staff (30 volunteers) worked in teams with 33 REU students and ~40 Upward Bound Math and Science (UBMS) high school students to present six nano and materials science themed booths at this annual one day community event attended by ~8000 people, with more than 1100 children counted at the science activities; All volunteers were trained in advance of the event; The mixed teams were purposefully structured to provide opportunities for potential networking and mentorship relationships to develop between volunteers; In partnership and support of a new local children’s science museum (Discovery Space of Central Pennsylvania), families were also encouraged to complete a science passport and an at-home experiment (reporting their results online) to become eligible for a prizes sponsored by Science-U and The Franklin Institute;

Girl Scouts: At a fall workshop hosted by Graduate Women in Science (GWIS), MRSEC graduate students presented materials science demonstrations in a session titled “Nanotechnology” to assist girls in earning there “Why in the World” patch (~35 upper elementary and middle school girls); At a summer space and astronomy themed weekend, MRSEC staff (and an interested undergraduate from the Society of Physics Students) engaged girls and their leaders in an outdoor “sense of scale” exercise in which a scale model of the solar system was then compared to a related sense of scale exploration on the micro and nano-scales.

Penn State “TailGreat”: During September 2011, in partnership with Penn State Athletics, Center members and student athletes (enrolled in STEM majors) engaged over 100 children and their families in three interactive science activities prior to a Penn State home football game; A group of child participants and student athletes were also featured guests at the pre-game pep rally and applauded for their pursuit of scholarship and interest in science (attended by ~3500 fans); Following the event, an at-home science challenge (“Will a golf ball float in the ocean?”) was promoted by the Nittany Lion Kids Club online (25 families submitted results); And as a result of this event, MRSEC learned that a neighborhood science club formed when a Kids Club member and her mother started talking about the science challenge at their morning bus stop. In response to a January 2012 follow-up email, the mother stated: “As for our Bus Stop Science Gang (love it), we have completed 5 separate days ... we're gearing up again soon ... We have up to nine kids from pre-school to 5th grade, and we've blown up marshmallows in the microwave, made raisins dance in seltzer and have had blow-dryer/ping pong ball contests to name a few.”
In 2012, the MRSEC will continue to participate in the annual events listed above, as well as support and explore new opportunities that may originate as a result of evolving partnerships. However, the Center has also committed to taking the lead on two brand new outreach programs:

**NanoDays:** As a recipient of the 2012 NISE Net kit, the MRSEC will partner with the Discovery Space of Central Pennsylvania children’s science museum to host 4 children’s workshops, a full day teacher workshop, and an evening Science Café during the week of March 24 – April 1, 2012; Additional collaborators thus far include the Eberly College of Science Outreach Office, the Materials Research Institute (MRI), and the Center for Nanotechnology Education and Utilization (CNEU).

**Women in STEM Mixer:** In order to better impact a population targeted within the Diversity Strategic Plan, the MRSEC has adopted a previously successful program from Penn State’s Women in the Sciences & Engineering (WISE) Institute (which no longer exists due to budget cuts); the mixer strives to engage faculty, research associates, post-docs, graduate students, undergraduates, and interested community and industry representatives in a facilitated and structured networking event to be held at the new Millennium Science Complex Building, home of the MRI.

**Center County Youth Service Bureau:** In support of an initiative by a faculty member at the Materials Characterization Lab at the MRI, the MRSEC will assist in delivering monthly one-hour programs to expose middle and high school at-risk youth to opportunities, experiences, facilities, instrumentation tools, and potential careers in the fields of materials and nano-scale science.

**K-12 Programs**

Due to the nature and structure of the Center, as well as the location of its facilities and members, outreach and education efforts that strive to directly reach and target K-12 audiences occur as a result of MRSEC partnerships with existing K-12 specific programs, as well as relationships that have evolved with teachers, parents, and school administrators. The following programs are supported by the MRSEC:

**Science-U Summer Camps:** Continuing a strong and long partnership, MRSEC contributed to two camp programs, Science Leadership (25 high school students) and Jr. Science Sleuths (50 2nd and 3rd graders); Overall support included assisting with curricular content, providing financial and staff support, and assisting with the recruitment of high school applicants from underserved and underrepresented groups for 7 MRSEC funded camp scholarships; MRSEC members also hosted a group of leadership campers for their group project and hosted a lively interactive mixer event, which has become an annual highlight of the Leadership camp;

**Park Forest Middle School STEM Fair:** MRSEC graduate students and post-doctoral fellows presented short materials science demonstrations and talked to young students at a local school event that engages and exposes students to current science topics of interest, local opportunities, and future careers in STEM fields (980 students enrolled);

**Ferguson Elementary Science Fair:** MRSEC staff engaged the Society of Physics Students (SPS) to honor a request received by a local elementary school to demonstrate static electricity with a Van der Graaff generator at the annual science fair attended by more than 50 students, plus their siblings and parents;
**Science-U BOOt Camp:** Graduates students volunteered to assist Science-U at this extremely popular annual Halloween (& Harry Potter) themed science program for 80 kids in upper elementary and middle school grades;

**Discovery Space of Central Pennsylvania:** Utilizing the museum exhibits that were developed in partnership with the Franklin Institute, MRSEC graduate students provided and presented cart-based demonstrations during the two inaugural opening events of this new local children’s science museum (July’s soft opening during the Arts Festival weekend saw 2,235 visitors, the Grand Opening debut on October 22nd reached ~900 visitors);

**Summer Experience in the Eberly College of Science (SEECoS):** In partnership with the tremendously successful Upward Bound Math and Science (UBMS) program (for low-income and first generation high school students from underrepresented and underserved populations), the SEECoS program provides a six-week hands-on research experience in a real laboratory setting; three MRSEC faculty members and their research groups each hosted a group of UBMS students and assisted them with their projects;

**St. Joseph’s Academy Catholic High School:** In partnership with the Eberly College of Science Outreach Office, MRSEC graduate students informed, educated, engaged, and entertained ~50 students, teachers, and administrators (at a small new Catholic high school that has limited resources) with a dynamic on-stage program that used multiple liquid nitrogen demonstrations to develop the basis of the Ideal Gas Law through the proper control of variables; Graduate students also talked personally with students about their science background and experiences, answered questions about school and career options, and encouraged students to consider scientific careers, interests, and knowledge.

**Undergraduate Research**

**Research Experiences for Undergraduates (REU):** The Center, in partnership with the Department of Physics, has been designated a REU site by the National Science Foundation Division of Materials Research (DMR 1062691). Undergraduate students majoring in physics, chemistry, material science, all branches of engineering, etc. and who have an interest in materials research were sought to apply. The student selection process involved an online application followed by the submission of 1-2 letters of recommendation and an official transcript. Applicants were reviewed by a committee and the best were selected with an emphasis on finding minority talent.

This program provided undergraduates the opportunity to participate in frontier materials physics and materials research at a major research facility. Students worked closely with a faculty member advisor, as well as graduate student and postdoctoral scholar mentors in their research groups. They experienced the challenge and excitement of a career in research (and sometimes the occasional frustrations, too). A team building event at the start of the program assisted in developing positive relationships within and between research groups. Required attendance at weekly Seminars ensured that students were informed about the broader scope of interdisciplinary research, career opportunities and educational strategies, ethics issues, etc. Additionally, students were provided with valuable professional development opportunities and training through their involvement in the Central Pennsylvania Festival of the Arts - Kids Day event (described above), an educational trip to the Franklin Institute science museum (where they participated in a set of interactive activities to learn about the development, design, and
implementation of museum exhibits, as well as the importance of continued efforts to engage public audiences through informal science education programs), and the large interdisciplinary Summer Research Symposium (a coordinated effort by several distinct summer research programs which required all students to present their summer research at a poster session and an individual 10-minute talk in an atmosphere that simulated a large professional conference experience).

The MRSEC supported the following students:

<table>
<thead>
<tr>
<th>Name</th>
<th>College or University</th>
<th>Advisor</th>
<th>Research Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacob Cox</td>
<td>Lock Haven University</td>
<td>Theresa Mayer</td>
<td>Synthesis of Metal Microwires for Dielectrophoretic Assembly Studies</td>
</tr>
<tr>
<td>Tyler Maunu</td>
<td>University of Minnesota Twin Cities</td>
<td>Jorge Sofo</td>
<td>Localization of Energy States in Hydrographene</td>
</tr>
</tbody>
</table>

The following MRSEC faculty hosted undergraduates in their laboratories:

<table>
<thead>
<tr>
<th>Name</th>
<th>Student</th>
<th>College or University</th>
<th>Research Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vincent Crespi</td>
<td>Teresa Hamill</td>
<td>University of Pennsylvania</td>
<td>Free Energy Calculations for Binary Crystal Structures Under the Conditions in Neutron Star Crusts</td>
</tr>
<tr>
<td>Venkatraman Gopalan</td>
<td>Aaron Foster</td>
<td>Oklahoma Baptist University</td>
<td>Germanium -Zinc Selenide Bragg Fiber for Transmitting 3.39 μm Infrared Light</td>
</tr>
<tr>
<td>Tony Jun Huang</td>
<td>Armanj Hasanyan</td>
<td>Virginia Institute of Technology</td>
<td>UV Polymerization to Fabricate Different Shaped Microstructures</td>
</tr>
<tr>
<td>Thomas Mallouk</td>
<td>Carlos Baez Cotto</td>
<td>University of Puerto Rico at Cayey</td>
<td>Tailoring of Light Scattering in Composite Microspheres for Spectrum-Splitting Solar Cells</td>
</tr>
<tr>
<td>Theresa Mayer</td>
<td>Jacob Cox</td>
<td>Lock Haven University</td>
<td>Synthesis of Metal Microwires for Dielectrophoretic Assembly Studies</td>
</tr>
<tr>
<td>Susan McKinstry</td>
<td>Mary Burkey</td>
<td>North Carolina State University</td>
<td>PZT Piezoelectric Films on Glass Substrates for Gen-X Imaging Systems</td>
</tr>
<tr>
<td>Suzanne Mohney</td>
<td>Jennifer Hajzus</td>
<td>Rensselaer Polytechnic Institute</td>
<td>Low-Resistance Ohmic Contacts to p-Type GaN</td>
</tr>
<tr>
<td>Nitin Samarth</td>
<td>David Myers</td>
<td>Covenant College</td>
<td>Avalanche Behavior of Interacting Magnetic Nano-islands</td>
</tr>
<tr>
<td>Nitin Samarth</td>
<td>Luis Pomales-Velázquez</td>
<td>University of Puerto Rico at Humacao</td>
<td>Characterization of the Epitaxial Growth on Bi2Se3 and Bi Thin Films on ZnSe</td>
</tr>
<tr>
<td>Ayusman Sen</td>
<td>Joshua Rosario</td>
<td>University of Puerto Rico at Cayey</td>
<td>Enzyme-Powered Nanomotors</td>
</tr>
<tr>
<td>Jorge Sofo</td>
<td>Tyler Maunu</td>
<td>University of Minnesota Twin Cities</td>
<td>Localization of Energy States in Hydrographene</td>
</tr>
<tr>
<td>Darrell Velegol</td>
<td>Elias Pabon</td>
<td>University of Puerto Rico at Cayey</td>
<td>Creating Flexible Colloidal Chains made from Flattened Spheres</td>
</tr>
</tbody>
</table>

It is worthwhile mentioning that, in addition to the REU program described above, MRSEC faculty were also actively involved in several other summer research experience programs for
undergraduates. Two faculty members advised students in the Chemical Energy Storage and
Conversion REU program hosted by the Department of Chemical Engineering, College of
Engineering; five faculty members were advisors for participants in the REU and 3M programs
hosted by the Department of Chemistry, College of Science; and two faculty members
supervised students in the REU program in Soft Materials hosted by the Materials Science and
Engineering Department, College of Earth and Mineral Sciences. Successful interdisciplinary
research requires awareness of, appreciation for, an interest in, and willingness for engaging a
variety of expertise. The strong involvement by PSU MRSEC faculty in these programs
demonstrates the extent to which the Center is, directly and indirectly, exposing and promoting
interdisciplinary research to the next generation of scientists and engineers.

Please note that the statistics reported for the REU program are somewhat complex, since they
involve an associated REU site grant, under which some of the students supported work with
non-MRSEC faculty. The program is offered in an integrated fashion and all students –
regardless of mentor – participate in the same career development activities. The students listed
above are those that work directly with MRSEC faculty. The numbers reported in Appendix C
(Number of Active Participants) includes all students in the REU program, and breaks out the
number with direct MRSEC support in a separate column. The numbers reported in the Diversity
section similarly include the entire REU site program (many of these diversity students are
mentored by MRSEC faculty); to find the numbers of these students with direct MRSEC support,
please refer to Appendix C.

Opportunities for Teachers

Research Experience for Teachers (RET): In partnership with the Department of Physics,
which has been designated a RET site by the National Science Foundation Division of Materials
Research (DMR 1062691), and MRI’s NanoFab facility, a member of the National
Nanotechnology Infrastructure Network (NNIN), the MRSEC provided multiple avenues of
support for the program. MRSEC postdoctoral fellow, Francelys Medina, coordinated all aspects
of the application and selection process, matched faculty advisors and projects with teachers,
confirmed seminar speakers, implemented formative and summative evaluations, provided
ongoing logistical and personal oversight as needed, and successfully secured a brand new bonus
for participating teachers: 3.5 graduate credits from Penn State, as well as 30 hours of
Pennsylvania Act 48 credit. Additional MRSEC support included faculty advisor participation,
funding for project materials, staff support for preparing presentations at the Summer Research
Symposium, and coordinating the REU/RET trip to the Franklin Institute science museum. At
the core of Penn State’s RET program is a focus and emphasis on conducting research, as
teachers engaged primarily with faculty and research groups in their laboratory settings.

The following teachers participated in the RET program:

<table>
<thead>
<tr>
<th>Name</th>
<th>School District</th>
<th>Advisor(s)</th>
<th>Research Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heath Stout</td>
<td>State College Area School District, Pennsylvania</td>
<td>Christine Keating</td>
<td>Assessment of Inhibition of Bacteria by Silver Colloid-Impregnated Bandages</td>
</tr>
<tr>
<td>Elinor Graf</td>
<td>Saint Hubbert High School For Girls, Pennsylvania</td>
<td>Christine Keating</td>
<td>Assessment of Inhibition of Bacteria by Silver Colloid-Impregnated Bandages</td>
</tr>
</tbody>
</table>
Middle school girls build and calibrate colorimeters to be used school-wide in future science investigations.

**Mini-Grant:** Due to the enthusiasm that developed as a result of his strong, positive RET experience, William Hughes, immediately implemented his summer project in his classroom with the assistance of MRSEC outreach funding for the materials he needed. In his Technology Education class (an elective course in which half the students are female, a common number which speaks volumes about his efforts to steer females towards STEM career pathways), 19 students assembled and calibrated colorimeters that ~300 8th grade students will utilize for wet chemistry, nano-scale prism and particles investigations during spring 2012 science classes. This project will also be presented at the Biannual Conference of Chemical Education (BCCE) occurring in August 2012.

**Evaluation & Assessment**

Keeping thorough and accurate records of all outreach events was a primary focus this past year. Being able to assess impact on both presenters and participants, as well as acknowledge and recognize the contributions made by MRSEC members, is of utmost importance. Developing a culture that actively participates in outreach and education programs, as well as values and understands the importance of them, requires opportunities for these experiences to occur, support for their implementation, appreciation and recognition of the efforts made by volunteers, and some form of assessment or evaluation of every program. When all of these pieces are systematically in place, willing and enthusiastic involvement develops, and judgments can be made to improve or alter efforts as appropriate. Records indicate that involvement and engagement by MRSEC faculty, research associates, postdoctoral fellows, and graduate students, is growing. Feedback from volunteers after each event or program was collected to gauge perspectives on impact, effectiveness, and ideas for improvement. All volunteers also earned and received token awards in appreciation and recognition of their efforts.

Both the REU and RET programs associated with the MRSEC collected extensive summative and formative evaluation data. The REU program completed an initial background survey, two summative progress surveys to assess the program while in progress, and a final post-survey. The RET program participated in a multi-site evaluation program conducted through Columbia University. Positive highlights include a definite sense of the worthwhile benefits of having research experience, as well as a better understanding of how independent and self-motivated one needs to be in order to produce in such an environment.
In an effort to continue to improve the Center’s evaluation and assessment efforts, the MRSEC has committed to participate in the 2012 Evaluation Planning Partnership with the Cornell Office for Research on Evaluation under NSF Award No. 0814364. The program involves a phase II trial of the Systems Evaluation Protocol for Assessing and Improving STEM Education Evaluation, where participants will pilot a self-guided, online version of the program known as the mySEP. Additionally, the Center has written a letter of support to Robert H. Tai (Curry School of Education, University of Virginia) for his NSF proposal regarding new evaluation tools for STEM education entitled “Project FOCIS: Framework for Observation and Categorization of Interest in Science”. In the event that this project is funded by NSF, the Center will utilize these survey instruments within our programs and engage in data collection.
7. Postdoctoral Mentoring Plan

The MRSEC hosts postdoctoral researchers in two distinct types of positions: research-focused postdoctoral fellows and also education/outreach postdoctoral officers. These two positions have a distinct character, but share many common mentoring goals. We begin by describing the elements in common to both types, and then describe the elements that are unique to each.

Each postdoctoral fellow, working in conjunction with appropriate lead faculty members (faculty research mentors or the Associate Director in charge of outreach), is expected to develop an Individual Development Plan (IDP). The IDP outlines long-term career goals and short-term objectives, identifies areas for specialized training, and facilitates effective communication of expectations between postdoc and mentors. The mentors provide the postdoctoral fellow with counseling tailored to his/her career goals in academia, industry or government. These plans are based on published best practices as presented in the National Postdoctoral Society mentoring toolkit. Depending on their interests and goals, the postdoctoral scholar is offered training opportunities ranging from research training to formal workshops, seminars, and informal mentoring. Key components of a mentoring plan include:

- Introduction to the local environment and campus-wide resources available to support their research, teaching, outreach and professional development.
- Participation in the Scholarship and Research Integrity program at Penn State to provide comprehensive training in the responsible conduct of research.
- Participating in a brown-bag lunch series (sponsored by the Penn State Postdoctoral Society) where speakers discuss leadership, professional ethics, work-life balance, conflict resolution, career paths in and outside of academia, entrepreneurship, applying for positions and negotiating start-up packages.
- Presentations in MRSEC seminars to develop communication and presentation skills.
- Guidance with regards to a journal club organized by the Penn State Graduate School to provide guidance on writing scholarly publications.
- Travel to at least one professional conference each year to present the results of research, develop professional relationships and network with colleagues.
- Networking with leaders in academia and industry by meeting with them during campus visits and at professional meetings.
- Attending seminars and workshops on how to identify funding opportunities and write competitive grant proposals that are offered by the Office of Postdoctoral Studies. Involvement in MRSEC-oriented proposal preparations at the Seed level and also related proposals (PREM, REU, etc.)
- Participating in seminars on improving teaching effectiveness offered by the Schreyer Institute for Teaching Excellence. Examples include “Understanding and Engaging Today’s University Student” and “The Future of Textbooks in the Digital Age.” Postdoctoral scholars who intend to pursue academic positions are encouraged to teach at least one undergraduate course in their academic discipline during their time in the Center, and to obtain formal evaluations from their students. This is a particular focus for the postdoctoral education/outreach officers (as described below) but the opportunity is available to all.

In addition, research-focused postdoctoral fellows participate in regular IRG-level and smaller-scale research meetings to present and discuss results, brainstorm future directions, and plan pub-
lications. Research postdocs are intended to act as “glue” within an IRG, interacting across individual research groups and thereby obtaining broad, interdisciplinary perspective and capabilities.

Education/outreach postdoctoral fellows typically have a distinct set of career goals, and our mentoring plan reflects these so that each postdoc can develop a compelling, balanced portfolio of experiences and accomplishments that cover the range of capabilities – teaching, grant writing, outreach, and research. To ensure that adequate mentoring is provided in teaching, we target co-teaching environments, either as one lecture section in a multi-track introductory course or as one of two instructors co-teaching an upper-level undergraduate course. Further mentoring is provided in the joint preparation of grant proposals: one prior outreach postdoc successfully obtained an NSF Discovery Corp fellowship; another led the effort to prepare and submit a successful REU site proposal. Future opportunities along these lines include the PREM, I-Corps, REU (renewal) programs and other venues. We also provide opportunities for education/outreach postdocs to maintain a research arm to their activities, hosted in a MRSEC lab. In this manner, they can build a compelling CV that demonstrates success in teaching, securing grant resources, publishing, and a portfolio of outreach efforts that span from museum/academia partnerships to designing curricula for summer camps, working with high school teachers, etc. In addition, all postdocs are encouraged and supported to attend disciplinary and professional development conferences and workshops. As a measure of success, the last four education/outreach postdocs have all secured permanent teaching positions, and our prior instructor-level education/outreach manager is now an associate dean.

This mentoring program is assessed by regular discussion and feedback on each IDP as well as by the success in achieving career goals both during and following the postdoctoral fellowship. The Center Director consults on an annual basis with the primary faculty mentors of each postdoc to monitor career progress and ensure that each postdoctoral fellow has a comprehensively supportive environment for career development.
8. Center Diversity – Progress and Plans

Broadening the participation of diverse individuals, institutions, and geographical areas within the Penn State MRSEC is a priority that guides multiple efforts and decisions. The Center has a history of success in this area because it realizes the accomplishment of such a goal is an ongoing challenge that requires continuous and consistent attention by its faculty. As a result, the Center has created a diverse membership and culture, as well as an environment that is encouraging, welcoming, and continuously seeking top talent from underrepresented and underserved groups. Productive, effective, and successful interdisciplinary research requires the creativity, knowledge, expertise, experience, and unique perspectives of diverse collaborators who cooperate efficiently, work diligently, and value the individual contributions of each member. The Center’s participation numbers by underrepresented minorities and women over the past eight years are summarized in Tables 1-4 below. While there is some year-to-year fluctuation because of the small number of individuals in each category, it is clear that progress has been made in engaging minority graduate students and postdocs. The representation of female graduate students and postdocs, and female and minority faculty have remained roughly constant over the years. The Center’s goal is not to just sustain the current participation of women and minorities, which is comparable to that of other centers in the MRSEC program, but to increase their percentages. As a result, the Penn State MRSEC is working to engage in new programs, efforts, and strategies, while continuing the diversity efforts that have positively resulted in participation from these groups currently, and in the past.

The geographical location of the Penn State MRSEC within Central Pennsylvania gives it a unique opportunity to impact a population that is underserved with opportunities, encouragement, and support to pursue success in STEM fields – the rural communities that surround State College. While not as often identified or historically connected to other underrepresented groups, and whose barriers to success are due more to cultural expectations and economic disadvantages than denial of access, this population is reachable and in need of outreach and educational support. As a result, the Center has been strategically seeking, developing, and becoming involved in new initiatives, programs, and partnerships that target, in particular, the young women and girls within these nearby communities.

We live in a global society, however, and the Penn State MRSEC is fully aware that its diversity efforts must extend far beyond the local community. The participation and engagement in MRSEC research, education, and outreach activities by diverse faculty, graduate students, undergraduates, K-12 teachers and students, communities, institutions, and industry partners from around the state, country, and globe are vital to both its own success, and its mission of making a broad, positive, and powerful impact. Yet, while technology connects the world and opens doors of opportunities to receive and impart knowledge and to establish a far reaching variety of relationships and partnerships, the successful advancement of the next generation of scientists and engineers also requires singularity of focus and deep attention to detail. Therefore, in addition to fostering and utilizing its current connections, the Center is also committed to engaging underrepresented minorities and women with a priority on depth as much as breadth. Balancing these sometimes competing strategies is vital to optimizing the Center's efforts and use of resources. Therefore, communicating and following an organized strategic plan, in which
all its members are engaged, is the method by which the Penn State MRSEC plans to progress and expand the participation of women and underrepresented minorities.

The tables below summarize the Center’s participation data within the last reporting period and historically. The longitudinal consistency of the numbers indicates the ongoing commitment and value placed by the Center on the importance of diversity.

<table>
<thead>
<tr>
<th>2011 Total</th>
<th>Women</th>
<th>Underrepresented Minorities</th>
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<tr>
<td>REU</td>
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</tr>
<tr>
<td>RET*</td>
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</tr>
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Table 1: Summary of 2011 participants by category of Women and Underrepresented Minorities

*Note: RET information is not included in the longitudinal data tables below.

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Table 2: Total Number of Penn State MRSEC participants by year and category

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</table>

Table 3: Number of Penn State MRSEC Women participants by year and category

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</tbody>
</table>

Table 4: Number of Penn State MRSEC Underrepresented Minority participants by year and category.
**Research Experiences for Undergraduates (REU):** Due to changes in funding levels available for REU students, fewer students were supported in 2011 than in previous years. Despite the reduction in support, the selection committee maintained its commitment to diverse participation in the program. The selection committee intends to stay focused upon this priority as it evaluates the pool of applicants for the coming year in both the REU and RET programs. Additional efforts are being made to widen the pool of applicants and develop stronger ties to institutions and organizations that serve underrepresented groups. These efforts are described below.

In cooperation with Alabama A&M University (AAMU), the Center submitted a collaborative proposal under the Partnerships for Research and Education in Materials (PREM) solicitation #NSF 11-562. A number of Center colleagues will partner with AAMU faculty in areas of mutual research interest within six sub-projects related to nanomaterials. Equipment and facilities will be available to partnering AAMU faculty and students for the successful completion of these collaborative projects. The partnership will also include an exchange of faculty and students, with special consideration to AAMU undergraduate students who are interested in the Penn State Physics-MRSEC REU program.

The Center has also maintained a continued presence at national conferences hosted by organizations dedicated to the advancement of underrepresented minorities in science. Through school visits with faculty and students, networking with attendees, and giving talks and presentations, the Center worked to inform and recruit undergraduates to both MRSEC affiliated summer research programs and opportunities for future graduate studies. These meetings included: MRSEC Directors/PREM meeting in Puerto Rico; Society for the Advancement of Chicanos and Native American in Science (SACNAS) conference in San Jose, California; Committee on Institutional Cooperation - Summer Research Opportunities Program (CIC SROP) conference at the Ohio State University; and the National Societies of Black & Hispanic Physicists (NSBP/NSHP) joint conference in Austin, TX.

**K-12 Initiatives:** Through the strong partnership that has developed with Penn State’s Science-U program, the MRSEC provided 8 scholarships to the Science Leadership Camp program for high school students. The selected students were chosen from geographical areas with large minority populations (New Haven, CT and Philadelphia, PA) as a result of new and established relationships with programs in these areas. Of the 8 recipients who attended, 5 were female and 5 were underrepresented minorities.

As part of a strengthening partnership between the MRSEC and the Summer Experience in the Eberly College of Science (SEECoS) research program for high school students, three MRSEC faculty each hosted a small group of minority students for a 6-week basic research project in their labs. The students are part of the tremendously successful Upward Bound Math and Science (UBMS) program (for ~40 low-income and first generation high school students from underrepresented and underserved populations). These UBMS students were also placed in teams with REU students, MRSEC faculty, and MRSEC graduate students to participate in a full day of science outreach during the local Arts Festival Kids Day event.
The Center’s Associate Director, Tom Mallouk, assisted in leading a one-day hands-on chemistry laboratory at the National Federation of the Blind (NFB) Youth Slam event in Baltimore (July 2011). Approximately 50 high school students who were blind or visually impaired performed an experiment on freezing point depression in which they learned to use the talking tools developed in the Independent Laboratory Access for the Blind (ILAB) project at Penn State.

Because of budget cuts, Penn State was forced to close its Women in Science and Engineering (WISE) Institute in 2011, and great concern was expressed by the local academic STEM community that it served. Center members participated in the discussion and took action to fill the void. In particular, MRSEC made the decision to adopt the Women in STEM Mixer program from WISE, and will implement it during the coming year. Also, as can be seen in the list of outreach events and activities in Section 6, specific efforts were made to partner (and initiate new connections) with organizations, programs, and events that focus upon female success in STEM. These groups include Graduate Women in Science (GWIS), the Girl Scouts, AAUW, and Penn State’s Commission for Women (CFW).

Plans for the next reporting period: The Center for Nanoscale Science will continue to emphasize and prioritize established, ongoing efforts to recruit and retain broad participation in its research and educational activities. The Center’s key strategies for the coming year are:

- Hold regular meetings of the MRSEC Diversity Committee and expand its connections and communication with diversity representatives, graduate admission committees, and REU selection committees within the interdisciplinary departments and colleges associated with the MRSEC
- Continue to have an active presence at national conferences hosted by societies dedicated to the advancement of underrepresented groups in science; maintain and initiate contact with institutions who also serve these groups
- Investigate the possibility of establishing and supporting a formal bridge program for incoming undergraduate minority and female students at Penn State who have expressed a commitment to the pursuit of a STEM major; seek opportunities to connect with current minority undergraduates to promote awareness about materials science as an important field of study and an exciting potential future career opportunity
- Continue to implement and support programs and initiatives that target female involvement in STEM fields, careers, research opportunities, and Center activities; make efforts to connect women from various stages along the career path, and include men in the conversation
- Continue to strengthen the collaborative outreach and education partnership that is currently developing with the Materials Research Institute as a result of their brand new state-of-the-art research facility; utilize this partnership as an opportunity to attract, support, and retain underserved minority and female students, postdoctoral fellows, research associates, and faculty
- Assuming a successful outcome for the PREM proposal, establish and implement the proposed projects, visits, and faculty/student exchanges
9. Knowledge Transfer to Industry and Other Sectors

The faculty of the Penn State MRSEC are engaged in a broad spectrum of activities with scientists and engineers in corporate and government laboratories within the U.S., and in exchanges and collaborations with international academic partners. These interactions include research collaborations, presentations at workshops and conferences, and patents and software. The MRSEC hosts visiting scientists and plays a key role in the overall industrial/technology transfer infrastructure of the University. There is also strong international component to collaborative research and outreach activities of the Center.

Penn State is a significant performer of industry sponsored research and as such maintains research relationships with companies and national laboratories across diverse fields. A key vehicle for enabling these relationships is the industry sponsored research projects agreement, which has been executed with more than 50 of the University’s leading industrial research sponsors, including many that sponsor MRSEC research. These bilateral agreements streamline the negotiation of individual sponsored research projects by addressing issues such as publication rights and intellectual property management in advance. In addition, in the past year Penn State has announced a new policy whereby the university will not assert IP rights over the products of industrially sponsored research. This policy should greatly facilitate academic-industry partnerships.

One of the important vehicles for collaboration with industry is the MRSEC’s Industrial Affiliates Program, now in its fourth year. Under this program, industrial sponsors become affiliate members of the Center by executing a sponsored research projects agreement and making a commitment to support sponsor MRSEC research at a minimum level of $25,000 annually, representing approximately half the cost of a graduate student researcher. Matching support for the student is provided by the Center. Students and faculty mentors serve as Center liaisons to each affiliate member, while working on a research project of mutual interest. Ongoing communication between the affiliate member, the students and supervising faculty members are expected. Scientists and engineers representing affiliate members may co-direct student thesis research, and Center students also serve in internships with affiliate members. The Center also provides fellowships for scientists and engineers representing affiliate members.

Research Collaborations with MRSEC Faculty

Here we briefly highlight three industry interactions in the past year, and enumerate many of the other collaborative relationships that MRSEC faculty held with external partners in 2010.

The IRG2 team on catalytic motors and pumps is pursuing potentially transformative research on the active pumping/transport of hydrocarbons within porous substrates. This work is supported by the Advanced Energy Consortium, which counts as members many of the major oil companies and oil services companies. It supports four graduate students within IRG2. The IRG has hosted industrial visits and has an active program of sample exchange with partners.

IRG4 is pursuing a unique opportunity to produce high-power infrared waveguides through deposition of Bragg mirrors onto the inner surfaces of optical fiber pores, using the high pressure deposition techniques pioneered by the IRG. This work involves a small startup company, KMLabs, which is in need of such waveguides for high-harmonic coherent supercontinuum x-ray generation.

Current processors rely on Si CMOS circuits. However, over nearly the last decade, there has been no significant improvement in the chip operating frequency. This ultimately limits chip
performance. A team at IBM has identified a possible means to circumvent this problem by using a piezoelectric materials to compress a piezoresistor, in which the electrical resistance is a strong function of pressure. The Trolier-McKinstry group at Penn State is working with IBM to prototype such a system. If success, the resulting device structure would enable significant improvements in both chip speed and in lateral device scaling. The research in IRG1 could be critical to making these emerging devices lead-free.

Furthermore, IRG4 is in the preliminary stages of developing ZnSe fiber lasers with the goal of forming a company at a later date. Also, Gopalan in IRG1 consults for Crystal Research, Inc., Fremont, CA and Eastman Kodak, Rochester, NY. IRG3 worked with Bandgap Engineering (Waltham, MA) on the growth of silicon nanowires for intermediate band solar cell devices. IRG4 worked with Lockheed Martin on the development of transformation optics lens technology. Needs for nanocar manipulation and single molecule spectroscopy in IRG2 led directly to modification of the STM software by RHK Technologies and its adoption in all its new systems.

Workshops, Awards and Faculty Presentations

Working with many MRSEC faculty, postdocs, and graduate students, The Franklin Institute (Philadelphia, PA) developed a kit of cart-based, hands-on museum activities called “Hidden Power: Energy, Electricity, and Efficiency.” Sixteen of these activity kits were produced and distributed to science and children's museums around the U.S. Vin Crespi, Darrell Velegol, and Kristin Dreyer assisted in training educators from the recipient museums to use the kits at a workshop in Philadelphia in October, 2011.

Duming Zhang received the Young Scientist Award at 39th Conference on the Physics & Chemistry of Surfaces & Interfaces, Santa Fe, New Mexico, January 2012.

TMS EMPMD hosted with two sessions at TMS 2012 Annual Meeting in honor of the Distinguished Scientist Award of Long-Qing Chen from IRG1.

Susan Trolier-McKinstry from IRG1 was recognized by the Ceramic Education Council Outstanding Educator award in 2011.

Visiting Corporate and International Scientists:

IRG4 hosted visitors from collaborators from University of Southampton Optoelectronics Research Centre, including Pier Sazio, Noel Healy, Priyanth Mehta and Anna Peacock for research on fiber materials and devices. IRG 4 collaborates with Detlef Smilgies at the Cornell CHESS beamline on X-ray scattering and surface characterization. Additional international connections to diverse institutions are enumerated in the International Activities section.

Industrial and Related Fellowships or Internships:

Banafsheh Keshavarzi – Ph.D. in chemical engineering, Spring 2011, currently a postdoctoral researcher at Penn State. She was selected to participate in the Ph.D. Career Development Program at Air Products and Chemicals. She will join Air Products and Chemicals in July 2012.

Helen He, a former MRSEC graduate student, is currently a Postdoc at the Advanced Light Source, Lawrence Berkeley National Lab. Rongrui He from IRG4 took a position at Intel. Sen in IRG2 has been made a Fellow of the Japan Society for the Promotion of Science for work on catalytic motors.
10. International Activities

The Penn State MRSEC has a substantial international component to its research and outreach program. In particular, the fiber-based research program in IRG4 benefits from a deep and long-term relationship with the University of Southampton, with provides critical expertise on the fabrication of the fiber platform. In addition, IRG3 has strong connections to China, particularly since several alumni of this IRG3 have recently taken up permanent positions there. Furthermore, a new research direction in IRG2 using ultrasonically powered motors was initiated through interactions with collaborators in France. IRG1 also has several important relationships with international collaborators, as outlined below. The MRSEC has also committed to supporting an international workshop on first-principles materials computation in the next year. Specific international activities in the past year include the following:

- Professor Tour from IRG2 was the Lady David Visiting Professor at Hebrew University in June, 2011.
- Professor Lin He from Beijing Normal University working on magnetic and electronic properties of low dimensional systems is a facilities user working in collaboration with IRG3.
- Mingliang Tian, Former Research Associate of IRG 3 has started his own group at the China High Magnetic Field Laboratory in Hefei, China. His research interest has strong overlap with IRG 3. He expressed an interest to continue to collaborate with IRG 3. This may involve exchange of students. Professor Tian also visits Penn state periodically.
- Jian Wang, former post-doc of IRG 3 has assumed his position at the International Center for Quantum Materials as an Associate Professor of Physics in Peking University. His research interests overlap that of IRG3 and there is a plan to send students from Peking university to the MRSEC.
- Tom Mallouk, along with graduate students Yang Wang and Wei Wang, worked with Drs. Mauricio Hoyos, Angelica Castro, Eric Clément, and Anne Rousselet at ESPCI and Université Pierre et Marie Curie in Paris on a comparison of the movement of bacteria and catalytic nanomotors in fluids and on the ultrasonic propulsion of nanomotors. Mallouk visited ESPCI, and Hoyos and Castro visited Penn State to give seminars and perform experiments.
- Prof. Mario Pantoja from the University of Granada collaborates with IRG4 to develop efficient electromagnetic modeling tools for complex nanowire antenna structures based on time domain moment methods. There have been in-person visits in the past and currently the collaboration is primarily electronic.
- Douglas Werner (IRG4) visited Queen Mary University of London, London, England, to participate in a “Workshop on Transformation Optics and Metamaterials”.
- IRG4 hosted visitors from collaborators from University of Southampton Optoelectronics Research Centre, including Pier Sazio, Noel Healy, Priyanth Mehta and Anna Peacock for research on fiber materials and devices
- IRG1 hosted a year-long visitor, Jiamian Hu from Tsinghua University in a collaboration on phase field modeling.
- IRG4 collaborates with Michael Zharnikov at the U. Heidelberg, Germany and Detlef Smilgies at the Cornell, CHESS beamline on Xray scattering and surface characterization.
- IRG1 collaborates with Anna Morozovska at the National Academy of Sciences, Ukraine on the analytical theory of ferroelectric domain walls.
11. Shared Experimental and Computational Facilities

The MRSEC is closely integrated with the facilities of the Penn State Materials Research Institute (MRI), which include the Penn State Nanofab, the Materials Characterization Laboratory (MCL) and Materials Simulation Center (MSC). The MRSEC’s relationship to MRI and its associated facilities is illustrated in the chart at the right. This integration and coordination ensure that MRSEC’s investments in fabrication, characterization and computation have maximal institutional impact. MRSEC faculty provide the leadership for many of these facilities, with Theresa Mayer serving as the Director of the Penn State Nanofabrication Laboratory and Jorge Sofo as the Director of the Materials Simulation Center. The MRSEC also works closely with the management of the MCL particularly as regards the MFRN effort and in the acquisition of major new equipment. The synergistic relationship among the MRSEC and these three user facilities also ensures that the strategic directions and investments of the core facilities are mutually beneficial and beneficial to the MRSEC research and educational missions. The MRSEC Central Facility Laboratory (CFL) dovetails with the MRI facilities, providing specialized instrumentation that primarily serves the research needs of the Center. All three user facilities are not only integral to the MRSEC research programs, but are also integrated into the MRSEC Summer REU/RET as well as other outreach programs that serve middle school girls, teacher workshops, and at-risk youth. The MRSEC continues as a component of the Materials Research Facilities Network (MFNR), providing access to facilities for partner institutions.

Both the Nanofab and MCL are cost recoverable user facilities with rates defined on the basis of maintenance, repair and staffing in accordance with federal cost-accounting procedures and are reviewed annually by the Office of the Corporate Controller. Both facilities are operated by professional full-time staff, who coordinate numerous educational and training activities which are highly integrated into formal courses offered by Penn State faculty. Beyond providing administrative leadership, MRSEC investigators play key roles in transferring cutting-edge research techniques to these widely accessible user facilities. External outreach is primarily accomplished via Penn State’s node of the NSF National Nanotechnology Infrastructure Network (NNIN), which supports professional staff who serve as liaisons with external industrial and academic users. MRSEC faculty member Theresa Mayer directs the NNIN. MRSEC faculty provide input into strategic planning for the fabrication and characterization facilities through faculty steering committees and focus groups centered around specific types of instrumentation or processes (e.g. optical spectroscopy, lithography, electron microscopy).

The MRSEC also supports the Materials Simulation Center (MSC), a University-wide facility providing education, support and research activities to help users incorporate simulation into their research programs, through regular contributions towards computational hardware. In 2011, the MSC sponsored several short courses and workshops on simulation/modeling software. In February/March of 2011, the MSC delivered an extended short course on “Density Functional
Theory and its Plane Wave Implementation”. These courses provide training to users of simulation code across the university, broadening accessibility to these tools. The MSC also hosts regular user group meetings organized around particular types of simulation, including, the Density Functional Theory User Group and the General RCC & MSC User Group. An effective sharing system managed and supported by RCC and the MSC helped MRSEC users to take advantage of the full potential of the whole cluster and resulted in numerous findings and publications with the help from MSC/MRSEC.

The MRSEC Central Facilities Laboratory (CFL) is comprised of several laboratories that contain instruments for advanced electrical and optical characterization and sample preparation. The low-temperature characterization facility is a unique user facility in the MRSEC network and houses a physical properties measurement system (PPMS) that allows for electrical transport and heat capacity measurements from 400 K down to 50 mK and under fields as high as 9 T, a $^{3}$He-$^{4}$He dilution refrigerator (12 mK to 400K, up to 9T), and a micromanipulated probe station (4-450 K; up to 3T). In 2011, the MRSEC acquired a helium recycling system which will provide major cost savings. The MRSEC also provided partial support towards a six source ion beam deposition system for alloy films. The CFL also has an optics laboratory housing several critical pieces of characterization equipment critical to the tasks of IRGs 4 and 1, including a Nd-YAG tunable nanosecond laser. Several of these instruments transitioned to the MCL optical characterization laboratory in 2011. The MRSEC facilities are available to other internal and external users, but are managed and funded directly by the MRSEC. In 2011, Moses Chan provided overall coordination of the CFL. The Executive Committee reviews the CFL operating policies and budget on a regular basis. The MRSEC Executive Committee also reviews and prioritizes equipment requests from the IRGs on an ongoing basis.
12. Administration and Management

The organizational structure of the Center is outlined in the chart below. Daily operations are managed by the Director, Vincent Crespi, who reports directly to the Senior Vice President for Research, Hank Foley. Consultation with Professors Foley and Schiffer (Associate VP for Research and member of IRG1) facilitate the MRSEC’s interdisciplinary and intercollegiate nature.

Center policy is developed by consultation of the full membership and is implemented by its Executive Committee. This committee currently consists of the Director Crespi, the Associate Directors Mallouk and Chan, the IRG leaders (Gopalan, Sen, Chan and Mayer), the Associate VP for Research Peter Schiffer, the Penn State Materials Research Institute (MRI) Director Carlo Pantano, Outreach Director Dreyer and Mohney (who replaced Dickey, the former Director of the Materials Characterization Lab). Mallouk, the prior Director, is currently overseeing the outreach portfolio. The Executive Committee is well connected to University administration in materials research through Pantano, Schiffer, and Mayer (who is also Director of the Penn State Nanofabrication Facility), and all members of the Executive Committee are also active in the research and/or outreach activities of the Center. Mallouk, Mayer, and Schiffer also serve on the MRI advisory board, further connecting the leadership of the Center and MRI. The Executive Committee meets approximately monthly, typically after the weekly MRSEC Seminar. While the scientific direction of the Center grows in a “bottom up” way by soliciting the most compelling research ideas from the full membership, the Executive Committee plays an important role in coordinating the review of new proposals and ensuring that the research portfolio undergoes continual renewal. The Executive Committee is also charged with deciding resource allocation for facilities, coordinating the response of the Center to new initiatives from NSF and within the University, and guiding major initiatives in industrial outreach, educational outreach and international programs.

The full membership of the MRSEC meets weekly on Mondays at the MRSEC Seminar. These well-attended lunch seminars are a regular forum for reviewing scientific progress, introducing new ideas and new members, advertising outreach opportunities, performing career development activities with students and postdocs, and forming collaborations with visitors. They are also a natural place to communicate issues that are discussed in the Executive Committee with the members of the Center. In addition to these seminars, the students, postdocs and faculty in each IRG meet approximately bi-weekly to discuss their current research progress and challenges in more detail. Usually, at least one member of the Executive Committee is engaged in the research project and is present at those meetings.

The Center has a strong commitment to diversity, and successfully includes women at all levels. While the recruitment of students and postdocs from under-represented groups is challenging in
central Pennsylvania, a growing number have been recruited to the Center. The MRSEC Diversity Committee, which includes the directors of diversity-focused initiatives in several Colleges, helps to coordinate recruitment at campus-wide. Members of the Diversity Committee include Mallouk (Associate Director and Chair), Ron Redwing, Francelys Medina (Educational Outreach Coordinator), Kristin Dreyer (Educational Outreach Manager), Hank McCoullum (Diversity Coordinator for the Eberly College of Science), Catherine Lyons (Associate Dean of Educational Equity for the College of Earth and Mineral Sciences), Mary Beth Williams (Graduate Admissions chair, Department of Chemistry), and Joan Redwing (MRSEC faculty and Graduate Admissions chair, Department of Material Science and Engineering).

The external Advisory Board of the Center is regularly reconstituted approximately every two years to best reflect the current research agenda of the Center. It is composed of scientists from other academic institutions, national laboratories, and companies. These have included directors, as well as facility and education coordinators, of other MRSECs and NSECs. In several instances, visits of our Advisory Board have resulted not only in valuable advice to the Center but also to productive collaborations and industrial connections, as well as sharing of best practices for facilities and outreach. Since the MRSEC just hosted a visit by the official NSF review panel, (which served a closely related purpose) there was no external advisory board meeting in 2011.

The Executive Committee oversees the IRGs and Seed projects of the Center, and through a competitive review process decides on how support will be allocated. Resources for research are allocated in a manner that is intended to maximize innovation, productivity, and collaboration. Within IRGs, funds are not distributed to individual faculty, but instead support students and postdocs who work on multi-investigator projects. This organizational scheme is reflected in the internal accounting in that cost centers are not allocated to individual faculty, but instead to IRGs as a whole with centralized appointment of students. A similar policy is applied to projects within IRGs and Seed projects: in a sense, every project in the MRSEC is a Seed. Students are often jointly advised by faculty. Postdocs, who typically number 1 or 2 per IRG, are expected to play a broader collaborative role than graduate students, acting as a scientific “glue” across an IRG. Faculty (with the exception of the Director and Associate Directors) receive no salary support from the Center, although some are granted release time by their Departments. Faculty who are not the official thesis advisors of students on a particular project typically collaborate and often co-advice them. The regular IRG meetings (and smaller ad hoc meetings of individual projects) promote these kinds of interactions. When projects are phased out of the MRSEC, care is taken to minimize the impact on the students involved to facilitate optimal career development. Because this system does not allocate funds to any particular faculty member, there is relatively little inertia to impede the inclusion of new faculty or the support of particularly promising new ideas in the IRGs. This flexibility has helped the IRGs change their course in response to new findings and challenges – historically, several IRGs have entirely renewed their research agenda via incorporation of especially successful Seed projects, for example. Many of the faculty are members of more than one IRG, and this confers synergy to the research projects. For example, work on semiconducting and superconducting nanowires in IRG3 is currently exploiting novel high-pressure synthesis ideas from IRG4.

In the past year, the MRSEC has implemented a modified version of the annual Seed selection process, to best position the MRSEC for the upcoming renewal cycle. First, the MRSEC held an open competition for a “New IRG Seed,” a larger-than-normal seed effort explicitly designed to nucleate a group that can – after ~12 month’s Seed support – articulate a compelling vision for
possible inclusion in the renewal proposal. (All existing and new IRGs will compete on an equal basis for inclusion in the renewal proposal). In addition, all existing IRGs were asked to submit an IRG Redirection Seed proposal. Funds to support this process were collected by a modest budget rescission from each of the IRGs: in essence, they were asked to “ask for their money back.” This structure focussed the minds of the IRG teams and led to a set of successful IRG Redirection Seeds, which have substantially restructured the MRSEC as a whole and opened up new initiatives for compelling, high-risk transformative research.

The Center has a collaborative role with three Institutes at Penn State (MRI, the Huck Institutes for the Life Sciences, and the Penn State Institutes for Energy and the Environment) in reviewing and supporting Seed Projects. The Institute directors (Carlo Pantano, Peter Hudson, and Tom Richard, respectively) participate in the review process, and the Institutes co-fund appropriate projects of mutual interest and high intellectual merit. The web-based submission and review process is modeled after Fastlane, with the Executive Committee and Institute directors providing written reviews and later meeting as a panel to select projects for support. This is a win-win arrangement for the Institutes and the Center. The Center is able to leverage substantial additional support for new projects and obtain review input from outside experts. The Institutes benefit from the broad competitive proposal solicitation and review, which historically has attracted 15 to 20 collaborative proposals from the Penn State materials research community. Projects selected in this process have generally been very successful, either as future IRG projects or as the beginning of multi-investigator collaborations that later become NIRTs, MURIs, or other major grants.

**Educational outreach** is a strong unifying theme in the Center. Participation is expected of all students and postdocs and is encouraged from all faculty. Our educational activities are overseen by Associate Director Tom Mallouk. Dr. Ronald Redwing, the prior Outreach Director in the Center, is now an Associate Dean at Penn State, although he maintains an active interest and involvement in recruiting members of underrepresented groups for the MRSEC REU program. The MRSEC is very fortunate to have recruited Kristin Dreyer, a former high school teacher, instructor in the Physics Department, and administer of the Penn State Women in Science and Engineering program, as a new Outreach Director. Postdoctoral fellow Francelys Medina is an educational outreach coordinator in the Center, currently specializing in the RET/REU program. Kristin Dreyer is the administrative point of contact for our collaborations with the Franklin Institute.

**Industrial outreach**, including workshops, personnel exchange, and joint support of students is overseen by Pantano, together with Paul Hallacher, the Director of Research Program Development in the Office of the Senior Vice President for Research. Hallacher works with Tanna Pugh, who is Director of Research-Technology Transfer, to develop collaborative agreements with companies as part of the MRSEC Industrial Affiliates program.

Center operations, including budgets, subcontracts, reports, site visits, seminars, website maintenance, and appointment of personnel are managed by two full time administrative staff, Denise Patton and Patricia Doroschenko. Their financial reports and budgets are coordinated with the Grants Office in the Eberly College of Science and with the University Office of Sponsored Programs.
13. List of Ph.D. students and postdocs graduating in 2011
(W= woman, M= minority)

Graduate Students

Banafsheh Keshavarzi received her Ph.D in Chemical Engineering, she is currently a postdoc at Penn State.

Bala Juluri Krishna received his Ph.D. and is currently at Pacific Integrated Energy, Inc.

Eftihia Vlahos (W) received her Ph.D in Material Science, she is currently a postdoc at Penn State.

Emil A. Hernadez-Pagan (M) received his Ph.D in Chemistry, currently he is a postdoctoral fellow at Vanderbilt University.

Fatima Toor (W) received her master degree in Electrical Engineering and is currently at the National Renewable Energy Laboratory.

Helen He (W) received her Ph.D in Material Science, currently she is a postdoc at Advanced Light Source, Lawrence Berkeley National Lab.

Jian Wang, Penn State Research Associate, is currently appointed as an Associate Professor of Physics at the International Center for Quantum Materials, Peking University, Beijing, China.

Mahesh Krishnamurthy received his Ph.D in Material Science, he is currently Intel Photonics Group.

Mingliang Tian, Penn State Research Associate, is currently appointed as a Professor of Physics, at the China High Magnetic Field Laboratory, Chinese Academy of Science and Technology.

Qian Xu received Ph.D in May 2011.

Raegan Johnson (W) received her Ph.D in Material Science, she is currently a postdoc at Penn State.

Rongrui He, a postdoc in Chemistry, took a position at Intel.

Sharis Minassian (W) received her Ph.D in Chemical Engineering.

Wenchong Hu received a Ph.D in Electrical Engineering and is currently at Intel.

Yong Zeng, a postdoc, in Electrical Engineering is currently a postdoc at Los Alamos National Laboratory.
14. Publications and Patents

IRG 1
A. Primary Support


B. Partial Support


C. Shared Facilities

None.

**IRG 2**

**A. Primary Support**


**B. Partial Support**


**C. Shared Facilities**


**IRG 3**

**A. Primary Support**


**B. Partial Support**


H. Yan, Y. Sun, L. He, J. C. Nie, and M. H. W. Chan, “Observation of Landau level–like...


C. Shared Facilities

None.

**IRG 4**

**A. Primary Support**


**B. Partial Support**


C. Shared Facilities


**EDUCATION/OUTREACH**

A. Primary Support

None.

B. Partial Support

None.

**SEED PROJECTS**

A. Primary Support


**B. Partial Support**


**C. Shared Facilities**


**Patents and Inventions**

None.
Kyle J. M. Bishop
Department of Chemical Engineering
158 Fenske Laboratory
University Park, PA 16802
Tel: (847) 354-1874
E-mail: kjmbishop@engr.psu.edu

Ph.D. 2009  Chemical Engineering, Northwestern University
B.S. 2003  Chemical Engineering, University of Virginia

2010 – present  Assistant Professor of Chemical Engineering
2009 – 2010  Postdoctoral Fellow, Harvard University

Five most relevant publications
B. Kowalczyk, K.J.M. Bishop, I. Lagzi, D. Wang, Y.H. Wei, S. Han, B.A. Grzybowski, Charged
nanoparticles as supramolecular surfactants for controlling the growth and stability of microcrystals.
Nature Mater. 10.1038/nmat3202 (2012).
H. Nakanishi, D.A. Walker, K.J.M. Bishop, P.J. Wesson, Y. Yan, S. Soh, S. Swaminathan, B.A.
Grzybowski, Dynamic internal gradients control and direct electric currents within nanostructured
K.J.M. Bishop, C.E. Wilmer, S. Soh, B.A. Grzybowski, Nanoscale forces and their uses in self-assembly,
Small 5, 1600-1630 (2009).
Y. Wei, K. J. M. Bishop, J. Kim, S. Soh, Bartosz A. Grzybowski, Making Use of Bond Strength and

Five other publications
H.Nakanishi, K.J.M. Bishop, B. Kowalczyk, A. Nitzan, E.A. Weiss, K.V. Tretiakov, M.M. Apodaca, R.
Klain, J.F. Stoddart, B.A. Grzybowski, Photoconductance and inverse photoconductance in films of
R. Klajn, K.J.M. Bishop, M. Fialkowski, M. Paszewski, C.J. Campbell, T.P. Gray, B.A. Grzybowski,
Plastic and moldable metals by self-assembly of sticky nanoparticle aggregates, Science 316, 261-264
(2007).
R. Klajn, K.J.M. Bishop, B.A. Grzybowski, Light-controlled self-assembly of reversible and irreversible
K.J.M. Bishop, B.A. Grzybowski, ‘Nanoions’: fundamental properties and analytical applications of
M. Fialkowski, K.J.M. Bishop, R. Klajn, S.K. Smoukov, C.J. Campbell, B.A. Grzybowski, Principles

Thesis and Postdoctoral Advisors: Bartosz A. Grzybowski, George M. Whitesides

Synergistic Activities: Education and Outreach: Curriculum development for chemical engineering
Chem. Letters, Nanoscale; Session chair, ACS Colloids, June 2009, New York. Recent Awards:
Outstanding Graduate Student Award, Northwestern University, 2008; Visiting Scholar, Abdus Salam
International Centre for Theoretical Physics, Trieste, IT, 2008; Northwestern University Fellow, 2008;
NSF Graduate Research Fellow, 2005-2008.
Enrique D. Gomez 106 Fenske Laboratory (814) 689-9394
Chemical Engineering University Park, PA 16802 edg12@psu.edu
2009 : Chemical Engineering, Princeton University
Ph.D. 2007 : Chemical Engineering, University of California, Berkeley
B.S. 2002 : Chemical Engineering, University of Florida
2009-present : Assistant Professor of Chemical Engineering, Penn State University

Five most relevant & five other publications

Thesis and Postdoctoral Advisors: Nitash P. Balsara, Professor of Chemical Engineering, University of California, Berkeley and Yueh-Lin (Lynn) Loo, Associate Professor of Chemical Engineering, Princeton University

16. Honors and Awards

Ashley DaSilva received the Alumni Associate Dissertation Award in 2012.

Ashley DaSilva received the Duncan Fellowship from the Penn State Physics Department in 2011.

Ashley DaSilva received the Eberly College of Science Diversity and Climate Award during 2011/2012.

Ashley DaSilva was awarded the East Asia and Pacific Summer Institutes Fellowship in 2011.

Ashley DaSilva received the 2011 Eklund Memorial Lecturership, Penn State University.

Tony Huang received the 2011 Penn State Engineering Alumni Society Outstanding Research Award.

Banafsheh Kesharvarzi was selected to participate in the Ph.D. Career Development Program at Air Products and Chemicals beginning July 2012.

Bala Krishna Juluri received First-Place in the Poster Competition at the ESM Today Graduate Research Symposium in 2011.

Bei Wang received the Duncan Fellowship from the Penn State Physics Department in 2011.

Brian Kiraly received the NASA Space Technology Research Fellowship in 2011.

Brian Kiraly received the NSF Graduate Research Fellowship in 2011.

Daniel Ahmed received the Young Investigator Best Poster Award at the 15th International Conference on Miniaturized Systems for Chemistry and Life Sciences.

Darrell Velegol was named a Fellow of the AAAS (American Association for the Advancement of Science) in 2011.

Duming Zhang received the 2012 Eklund Memorial Lecturership, Penn State University.

Duming Zhang received the Young Scientist Award at 39th Conference on the Physics & Chemistry of Surfaces & Interfaces, Santa Fe, New Mexico in January 2012.

Jazmin Godoy-Vargas received the Harry B. Weiser Research Award in recognition of research excellence.

Jiamian Hu received the MRS Graduate Student Gold Medal Award in 2011.

Jian Wang received Fellow of the China Thousand Talents Program for Young Scientists in 2011.

Justin Sparks was awarded an Apple Fellowship by the Penn State Chemistry Department.

Long-Qing Chen received the TMS EMPMD (Electronic, Magnetic, Photonic Materials Division Distinguished Scientist Award in 2011.
Mahesh Krishnamurthy received the CSR Division Recognition Award from Intel in 2012.

Michael Lapsley received Third-Place in the Presentation Competition at the ESM Today Graduate Research Symposium in 2011.

Raymond Schaak received the 2011 National Fresenius Award.

Steven Lin received the Rustum and Della Roy Innovation in Materials Research Award at Penn State 2011.

Shahrzad Yazdi received Third-Place in the Poster Competition at the ESM Today Graduate Research Symposium in 2011.

Susan Trolier-McKinstry won the Ceramic Education Council Outstanding Educator Award in 2011.

Qian Xu received the Melvin P. Bloom Memorial Outstanding Doctoral Research Award in Electrical Engineering at Penn State in 2011.

Xiaoyun Ding received the Innovation Award in Presentation Competition at the ESM Today Graduate Research Symposium in 2011.

Yijia Gu received the Newnham Graduate Student Excellence Award in 2011.

Yi Zhang won the Microscopy Society of America (MSA) Presidential Award in 2011.