

PENNSTATE



MRI

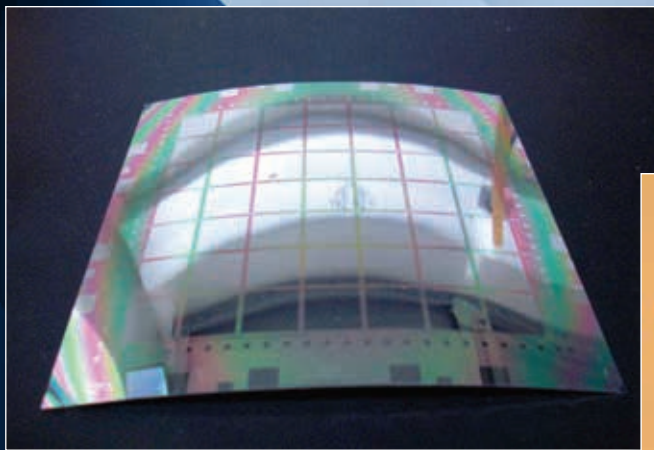
FOCUS

on MATERIALS

MATERIALS RESEARCH INSTITUTE BULLETIN

FALL 2014

Smart Materials



Focus on Materials is a bulletin of the Materials Research Institute at Penn State University. Visit our web site at www.mri.psu.edu

Clive A Randall, *Interim Director of the Materials Research Institute and Professor of Materials Science and Engineering*
N-221
Millennium Science Complex
University Park, PA 16802
(814) 863-1328
car4@psu.edu

Robert Cornwall, *Managing Director of the Materials Research Institute*
N-319
Millennium Science Complex
University Park, PA 16802
(814) 863-8735
rgc5@psu.edu

Walt Mills, *editor/writer*
N-358
Millennium Science Complex
University Park, PA 16802
(814) 865-0285
wem12@psu.edu

Mark Passmore, *graphic design*
Passmore Design
(814) 353-8853
passmoredesign@comcast.net

This publication is available in alternative media on request.

Penn State is an equal opportunity, affirmative action employer, and is committed to providing employment opportunities to minorities, women, veterans, individuals with disabilities, and other protected groups. Nondiscrimination: <http://guru.psu.edu/policies/AD85.html>

U.Ed. RES 15-13

Message from the Director



Clive A Randall

Pantano Steps Down After 16 Years at MRI Helm

The founding director of the Materials Research Institute, Carlo Pantano, has returned to full-time research and teaching after 16 years of leadership in interdisciplinary materials research at Penn State. Carlo is a distinguished professor of materials science and engineering, and an internationally recognized expert in glass research with a special interest in the nature of glass surfaces. As of September 1, 2014, Clive Randall, professor of materials science and engineering and long-time director of the Center for Dielectric Studies and current co-director of the Center for Dielectrics and Piezoelectrics, has stepped in as MRI's interim director.

During Carlo's tenure, MRI grew from an institute that existed largely on paper to one that now provides services and expertise to hundreds of companies and hands-on training to thousands of students. MRI faculty researchers now number well over 200 members across multiple science and engineering disciplines. The shared user facilities for nanofabrication and materials characterization are now easily accessible to all researchers in a new state-of-the-art research building on central campus that will assure Penn State's leadership in materials research into the 21st century.

"Material research at Penn State has had many great leaders over the years, and Carlo has been this generation's leader — showing a vision to blend the interdisciplinarity of the field in new ways, especially in regard to the crossover into life sciences. He also put into place the general user facility model for MRI that is now the model for many other top tier universities. He also made major contributions in strategic cluster hires to underpin the faculty in the material field at Penn State. Finally, through tireless efforts working with multiple people at the university, he championed the construction of the Millennium Science Complex – a building with laboratories and core facilities that impress scientists from all over the world. Carlo, thank you for your leadership – the materials community at Penn State and beyond is highly indebted to your vision, and we will all benefit from your work in years to come."

Sincerely,

Clive A Randall

*Interim Director of the Materials Research Institute
And Professor of Materials Science and Engineering*

To access the materials expertise at Penn State, please visit our Materials Research Institute website at www.mri.psu.edu or the Office of Technology Management website at <http://www.research.psu.edu/offices/otm>

CONTENTS

IN THIS ISSUE: SMART MATERIALS

4 Research Snapshots

Brief reports on illusion coatings, pumps-on-a-chip, two-dimensional materials, pixel engineering, and a top innovator under 35

11 Smart Materials Fold into Origami Shapes

An ancient art form finds a new purpose

16 Undergraduate Summer Researcher Contributes to Futuristic Space Mirror

A visiting undergrad may see her work on smart materials rocket into orbit

18 A Renewable BioPlastic Made from Squid Proteins

It's self-healing, biodegradable, and may end up in your 3D printer.

21 Materials Other Than Silicon for Next Generation Electronic Devices

What does it take to make the next generation transistor? A grad student struggles to find out.

24 Rethinking the Basic Science of Graphene Synthesis

A friendly wager corrects a 150 year old mistake.

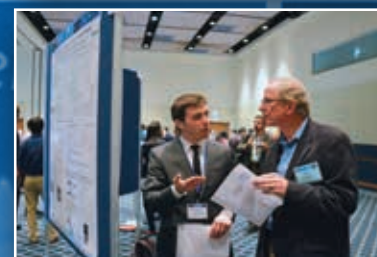
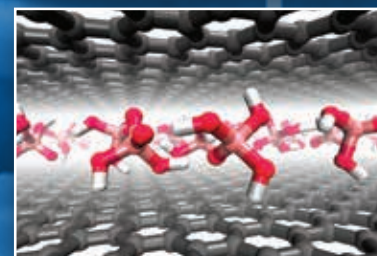
26 FACULTY SPOTLIGHT

Allison Beese, A Lot Still to Learn About Steel

In her lab, the young researcher studies advanced steels and tests 3D printed metals.

30 Industry and Researchers Meet at Materials Day

A recap and photos from a very successful Materials Day event

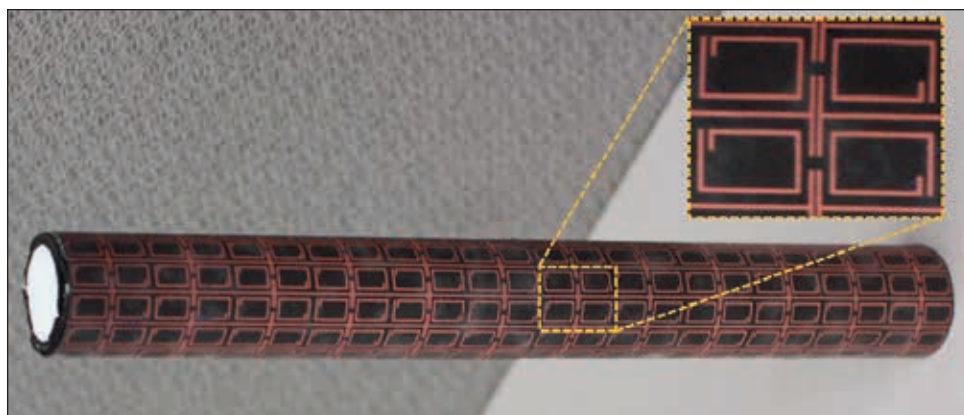


Cover: From top, clockwise – Thermoplastic squid protein, magnetic smart material, piezoelectric space mirror



Snapshots are brief summaries of significant materials-related breakthroughs by MRI researchers. More information is available by visiting the links at the end of each summary.

TAILORED FLEXIBLE ILLUSION COATINGS HIDE OBJECTS FROM DETECTION



Antenna covered with copper patterned dielectric substrate creates a flexible metasurface that acts as an illusion coating, cloaking the antenna or making it appear to be something entirely different. Credit: Zhibao Jiang/Penn State

Researchers in the Department of Electrical Engineering have developed a new type of metamaterials coating that can either cloak an object or create the illusion that the coated object is something entirely different. Using their coating, antennas and sensors could be made invisible or deceptive to remote inspection while still communicating with the outside world, something not currently possible with other cloaking devices.

Zhi Hao Jiang, postdoctoral fellow in electrical engineering, Penn State, and Douglas H. Werner, John L. and Genevieve H. McCain Chair Professor of Electrical Engineering, employ what they call

“illusion coatings,” which consist of a series of copper, geometric patterns placed on a flexible substrate using standard lithographic methods currently used to create printed circuit boards. The flexible coated substrate is bent around the object to be cloaked. This method of manufacture is low cost and well established. Each illusion coating must be designed for the specific application, but the designs are optimized with bio-inspired algorithms. The designs were experimentally verified by cloaking a nearly foot-long copper cylinder with a coating that mimicked a cylinder made of

Teflon. They report their research in *Advanced Functional Materials*.

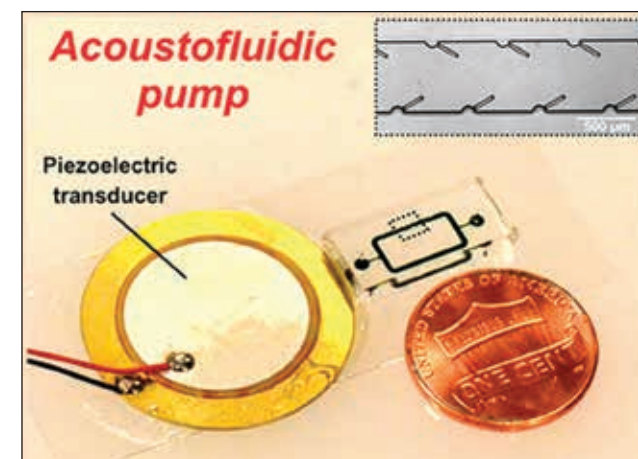
“The demonstrated illusion/cloaking coating is a lightweight two-dimensional metasurface, not a bulky three-dimensional metamaterial,” said Werner. “This work paves the way for practical artificially engineered material coatings with exotic and versatile scattering control capabilities that would enable a wide range of applications throughout the entire electromagnetic spectrum.”

Illusion coatings could be used for things other than hiding. They could enhance the way radio frequency ID tags work or could redistribute energy in different, controlled patterns making things more visible rather

than less visible. The materials shielding ability can also be used to protect any type of equipment from stray or intentional electromagnetic interference.

The National Science Foundation supported this work through the Center for Nanoscale Science, a Materials Research Science and Engineering Center at Penn State. Contact Douglas Werner at dhw@psu.edu.

Condensed from a news story by Andrea Elyse Messer at <http://www.mri.psu.edu/news/>.



An acoustically powered pumping device with 250 micron long oscillating structures driven by a piezoelectric transducer mounted on a glass slide. Credit: Po-Hsun Huang and Tony Jun Huang, Penn State

COST-EFFECTIVE, HIGH-PERFORMANCE MICROPUMPS FOR LAB-ON-A-CHIP DISEASE DIAGNOSIS

Researchers at Penn State have demonstrated an acoustofluidic pump powered by a piezoelectric transducer about the size of a quarter. This reliable, inexpensive, programmable pump is a crucial feature for lab-on-a-chip devices that could make the diagnosis of many global life-threatening diseases easy and affordable.

“The field of microfluidics and lab-on-a-chip technologies has the potential to revolutionize the healthcare industry with cost-effective, high-performance miniature biomedical diagnostic devices. Despite its tremendous potential, the field has only delivered very limited numbers of products and tools for real-world applications. One of the reasons is that it is difficult to fabricate micropumps that are simple and inexpensive, yet reliable and effective,” said Tony Huang, professor of engineering science and mechanics in Penn State’s College of Engineering.

Huang and his team demonstrated that with a smart microfluidic design, low-power acoustic waves could deliver fluids precisely and reliably. The permanent equipment for the total lab-on-a-chip system, including off-the-shelf electronics, could cost as little as \$20-\$30 to make, and the disposable chip could cost as little as 10 cents, Huang said. Although slightly more expensive than paper-based diagnostics -- such as home pregnancy tests -- the system is far more versatile and precise, enabling quantitative analysis of, for example, HIV, hepatitis, cancer, infectious diseases, cardiovascular diseases, and nutritional deficiency.

The pump works by oscillating a series of thin sharp-edge structures hundreds of micrometers in length that have been constructed onto the sidewall of a microfluidic channel made of PDMS, a widely used polymer. A miniaturized piezoelectric transducer, similar to the kind used in medical ultrasound, is the source of the oscillations. In the present work, reported online in the journal *Lab on a Chip* on September 4, 2014, a silicon mold of the device and the sharp-edged structures on its sidewall were first created using a deep silicon etch tool in the Penn State Nanofabrication Laboratory, followed by PDMS casting of the device. In the future, Huang said, the

devices and chips could be created using standard automated machine tools controlled by computers (CNC) for scalable manufacturing.

“Our pump is quite unique,” said Huang. “It’s reliable and programmable, with a minimum of hardware, yet highly precise. The flow rates can be tuned across a wide range, from nanoliters per minute to microliters per minute. I don’t see anything out there with our characteristics.”

The research was supported by the National Institute of Health, the National Science Foundation, and the Penn State Center for Nanoscale Science. In addition to Prof. Huang, the contributors to the paper in *Lab on a Chip*, “A reliable, programmable acoustofluidic pump powered by oscillation sharp-edge structures,” were graduate student and lead author Po-Hsun Huang, Nitesh Nama, Zhangming Mao, Joseph Rufo, Yuchao Chen, Yuliang Xie, Cheng-Hsin Wei, all graduate students at Penn State, post-doctoral researcher Peng Li, and Lin Wang of biotech start-up Ascent Bio-Nano Technologies Inc. Penn State has applied for a patent on the device.

Prof. Huang can be contacted at juh17@psu.edu.
Huang Lab: <http://www.esm.psu.edu/~juh17/>

THE NATIONAL SCIENCE FOUNDATION FUNDS THREE PENN STATE TEAMS TO STUDY TWO-DIMENSIONAL MATERIALS

Through the National Science Foundation’s Emerging Frontiers in Research and Innovation (EFRI) program, Penn State has been awarded \$4 million over the next four years to lead two teams of investigators and support members of a third team in the new field of 2D crystals and layered materials.

A material that is only a single atomic-layer thick can have completely different properties than its bulk counterpart. A new field of nanoscale science and engineering is emerging to study the wide variety of two-dimensional materials and what happens when they are stacked one on top of the other. Potential

applications include energy harvesting and storage, sensing, electronics and photonics, and bioengineering.

“There is a lot of interest in 2D materials beyond graphene, especially when considering stacking to form heterostructures because they can lead to phenomenal properties,” said Joshua Robinson, Corning Faculty Fellow of Materials Science and Engineering and associate director of Penn State’s Center for Two-dimensional and Layered Materials (2DLM). “I think we have a variety of excellent ideas in these novel materials, which is why we did so well with the EFRI.”

The EFRI awards fund interdisciplinary teams of researchers in rapidly advancing fields of fundamental engineering research. The 2014 awards, called 2-DARE, for Two-dimensional Atomic-layer Research and Engineering, were awarded to nine teams in the U.S., three of which include Penn State researchers.

- “2D Crystal Formed by Activated Atomic Layer Deposition” is led by Joan Redwing, professor of materials science and engineering and electrical engineering, with co-PIs Ying Liu, Nasim Alem, Thomas Jackson and Suzanne Mohny, all faculty at Penn State. The award is for \$1,964,494.

“Our project is aimed at developing Chemical Vapor Deposition (CVD) and Atomic Layer Deposition (ALD) processes to synthesize 2D materials. The 2D crystal films will be explored for applications in thin film electronics and superconductivity,” said Joan Redwing.

- “Ultra-low Power, Collective-state Device Technology Based on Electron Correlation in Two-Dimensional Atomic Layers” is led by Joshua Robinson with Co-PIs Suman Datta and Roman Engel-Herbert of Penn State, James Freericks, Georgetown University and Eva Andrei, Rutgers University. The award is for \$2,000,000.

“This program will develop a ‘post silicon’ transistor based on the principal of strong electron correlation

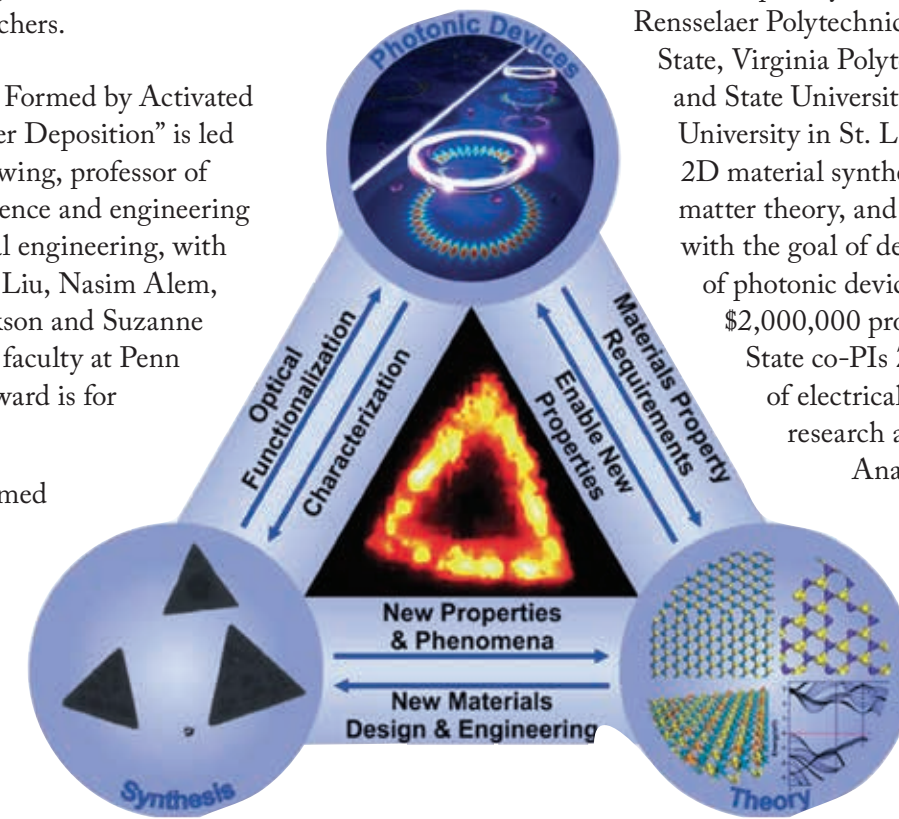
and associated phase transitions in two-dimensional materials,” said Robinson.

In addition, a third funded project, “Crystalline Atomically Thin Layers for Photonic Applications,” is a multidisciplinary collaboration between Rensselaer Polytechnic Institute, Penn State, Virginia Polytechnic Institute and State University, and Washington University in St. Louis investigating 2D material synthesis, condensed matter theory, and optical engineering, with the goal of developing a new class of photonic devices. Led by RPI, this \$2,000,000 project includes Penn State co-PIs Zhiwen Liu, professor of electrical engineering, and research associate in physics Ana Laura Elias Arriaga. The Penn State subaward is \$740,000.

“The goal of our project is to study the nonlinear optical properties of two-dimensional transition metal dichalcogenides and investigate their

photonic applications. These 2D materials have very large optical nonlinearity, and, for example, can produce strong second harmonic generation. The combination of their novel optical properties and atomic thickness creates a unique opportunity for using these materials to ‘dress’ photonic devices and provide new functionalities,” Zhiwen Liu said.

“2D expertise is very diverse at Penn State and includes electronics, bio, optics, synthesis, characterization and theory,” said Mauricio Terrones, director of the 2DLM Center and professor of physics, chemistry and materials science and



Schematic rendering for the project “Crystalline Atomically Thin Layers for Photonic Applications” Image Provided

engineering. “Including students, post-docs and faculty, we have about 50 people involved.”

With recent publications in high impact journals, such as *Nature Chemistry*, *Nature Communications*, *Nature Materials*, *Nano Letters* and *ACS Nano*, Penn State researchers are taking a leading role in the exploration of 2D materials, Terrones said. Recently, the Department of Physics hired two new faculty members to complement the expertise already available, he added. In addition to the National Science Foundation EFRI 2-DARE awards, 2DLM Center faculty have been

successful with several other high profile awards from the Army, Air Force, and Defense Threat Reduction Agency and have recently put an emphasis on industry-driven research through a variety of industrial partnerships.

Contact Details:

Joshua Robinson: jrobinson@psu.edu

Joan Redwing: jmr31@psu.edu

Mauricio Terrones: mut11@psu.edu

Zhiwen Liu: zliu@engr.psu.edu

PIXEL ENGINEERED ELECTRONICS HAVE GROWTH POTENTIAL

A little change in temperature makes a big difference for growing a new generation of hybrid atomic-layer structures, according to scientists at Rice University, Oak Ridge National Laboratory, Vanderbilt University and Pennsylvania State University.

Rice scientists led the first single-step growth of self-assembled hybrid layers made of two elements that can either be side by side and one-atom thick or stacked atop each other. The structure’s final form can be tuned by changing the growth temperature.

The discovery, reported in *Nature Materials*, could lead to what Rice materials scientist Pulickel Ajayan calls “pixel engineering”: atomically thin semiconductors with no limit to their potential for use in optoelectronic devices.

The researchers led by Ajayan and Wu Zhou, a materials scientist at Oak Ridge, discovered the interesting new composites when they combined the growth of two-dimensional molybdenum disulfide and tungsten disulfide through chemical vapor deposition. In this process, specific gases are heated in a furnace, where their atoms gather in an orderly fashion around a catalyst to form the crystalline material.

High-temperature growth – about 850 degrees Celsius (1,563 degrees Fahrenheit) – yielded vertically

stacked bilayers, with tungsten on top. At lower temperatures, about 650 degrees C (1,202 degrees F), the crystal lattices preferred to grow side by side. The interfaces in either material are sharp and clean, as seen under a scanning electron microscope and in spectroscopic studies.

According to co-author Mauricio Terrones of Penn State, “This paper describes for the first time the possibility of producing sharp hetero-interfaces with Transition Metal Dichalcogenides (TMDs). Basically, we can join covalently two different semiconducting materials with different energy band gaps and light emission properties. All this happens within one monolayer (an atom thick layer). It is the first indication that sharp interfaces with a TMD can be constructed. What is more amazing is that the interface does not have defects or grain boundaries. The whole system is monocrystal and all the atoms are oriented in only one direction.”

In addition, the researchers found novel phenomena, namely the generation of excitons (electron-hole pairs) from these interfaces of two materials. They believe that these unique hetero-monolayers could have very novel applications in photosensors, light sources, new ultra-fast lasers, opto-electronic devices, and more. The researchers believe that they can now build a perfect

atomic circuit based on 2D-heterojunctions, which are components of electronic devices. They could then try to contact these 2D materials with metallic contacts (for instance graphene, a 2D hexagonal honeycomb) and construct perfect 2D devices. The optical properties of these materials are also fascinating, and they are now trying to understand the physics of them.

“Our goal is to build fully functional electronic devices on a single plane, or maybe a few layers,” added Penn State’s Terrones. “What we’ve accomplished means that pretty much any architecture for devices is now possible on a single atomic layer. And that’s remarkable.”

The Army Research Office, the Department of Energy, the National Science Foundation, the Microelectronics

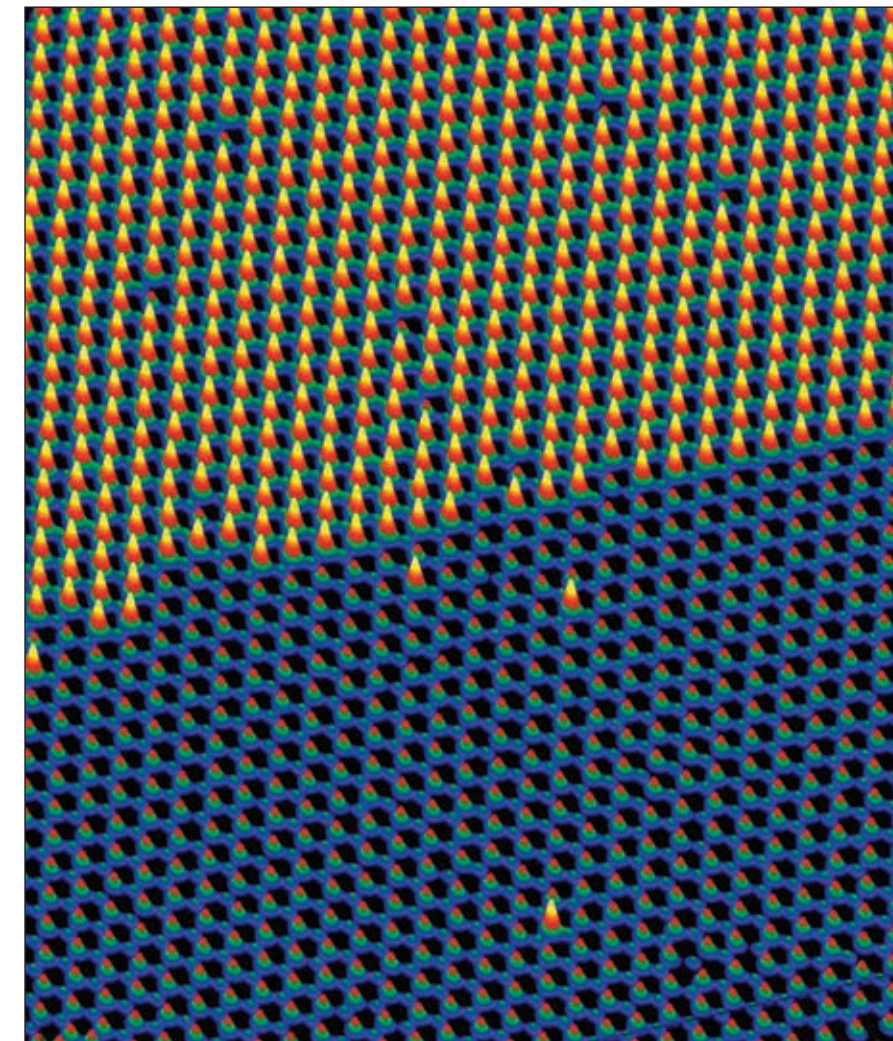
Advanced Research Corp., the Defense Advanced Research Projects Agency, the U.S. Office of Naval Research and the Ministry of Education Academic Research Fund and Silicon Technologies Center of Excellence, Singapore, supported the research.

Mauricio Terrones is a professor of physics, chemistry, materials science and engineering at Penn State and director of the Center for 2D and Layered Materials. Contact him at mut11@psu.edu.

From a press release from Rice University and Penn State

Visit the 2DLM website at

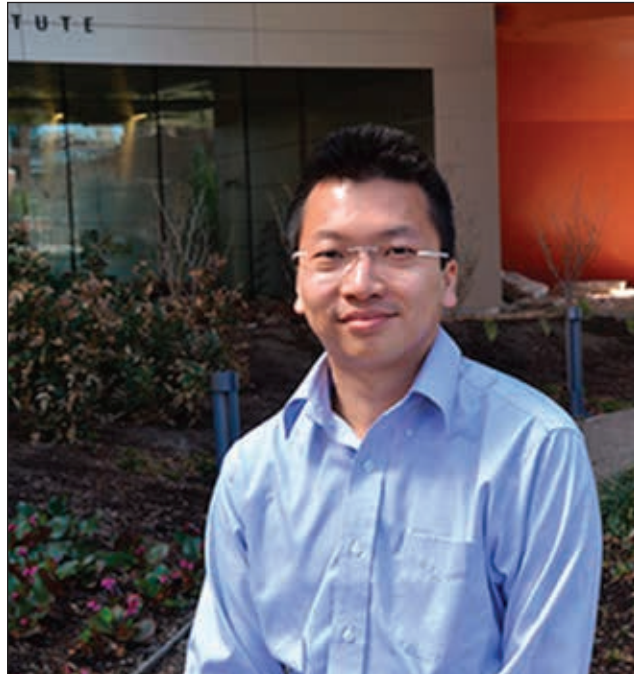
<http://www.mri.psu.edu/centers/2dml/>



This image shows the interface between elements of the in-plane material created by scientists at Rice University and their colleagues. Tungsten disulfide (orange) and molybdenum disulfide (blue) molecules self-assemble into either single- or multiple-layer materials, depending on growth temperature.

Credit: Yongji Gong and Junhao Lin, Rice University

WONG NAMED ONE OF WORLD'S TOP "INNOVATORS UNDER 35" BY MIT TECHNOLOGY REVIEW



Tak-Sing Wong, assistant professor of mechanical engineering and head of Penn State's Laboratory for Nature-Inspired Engineering, has been selected as one of the world's top Innovators Under 35 by *MIT Technology Review*.

Each year since 1999, *MIT Technology Review* has named exceptionally talented young innovators under the age of 35 whose work has the greatest potential to transform the world.

Wong's research interests cover a broad area of micro/nanoengineering, interfacial phenomena and biologically inspired engineering with applications in materials science, biomedicine and energy.

He focuses on ways to design and develop a new class of biologically inspired interfacial materials with multi-functional characteristics. These bio-inspired materials are based on the surface engineering principles of a number of plant, insect and animal species, with the latest example of pitcher plant-inspired super slippery surfaces.

Wong and the other young innovators will be profiled in the September/October issue of *MIT Technology Review* magazine, which is online at <http://www.technologyreview.com> and available on newsstands worldwide on Sept. 2. They will be honored in late September at the annual EmTech MIT conference in Cambridge, Massachusetts.

"Over the years, we've had success in choosing young innovators whose work has been profoundly influential on the direction of human affairs," said editor in chief and publisher Jason Pontin. "Previous winners include Larry Page and Sergey Brin, the co-founders of Google; Mark Zuckerberg, the co-founder of Facebook; Jonathan Ive, the chief designer of Apple; and David Karp, the creator of Tumblr. We're proud of our selections and the variety of achievements they celebrate, and we're proud to add Tak-Sing Wong to this prestigious list."

Earlier this year, Wong was selected for an early CAREER award from the National Science Foundation, and he has been invited to participate in the National Academy of Engineering's U.S. Frontiers of Engineering Symposium this September.

His work on bio-inspired surfaces was recognized as one of the Best Inventions using Biomimicry in 2011 and the 2012 R&D 100 Award for the world's top 100 technical innovations of the year.

A Penn State faculty member since 2013, Wong received his bachelor of engineering degree in automation and computer-aided engineering from the Chinese University of Hong Kong, his doctorate degree in mechanical engineering from the University of California, Los Angeles, and completed his postdoctoral research at the Wyss Institute at Harvard University.

Story from Penn State Today

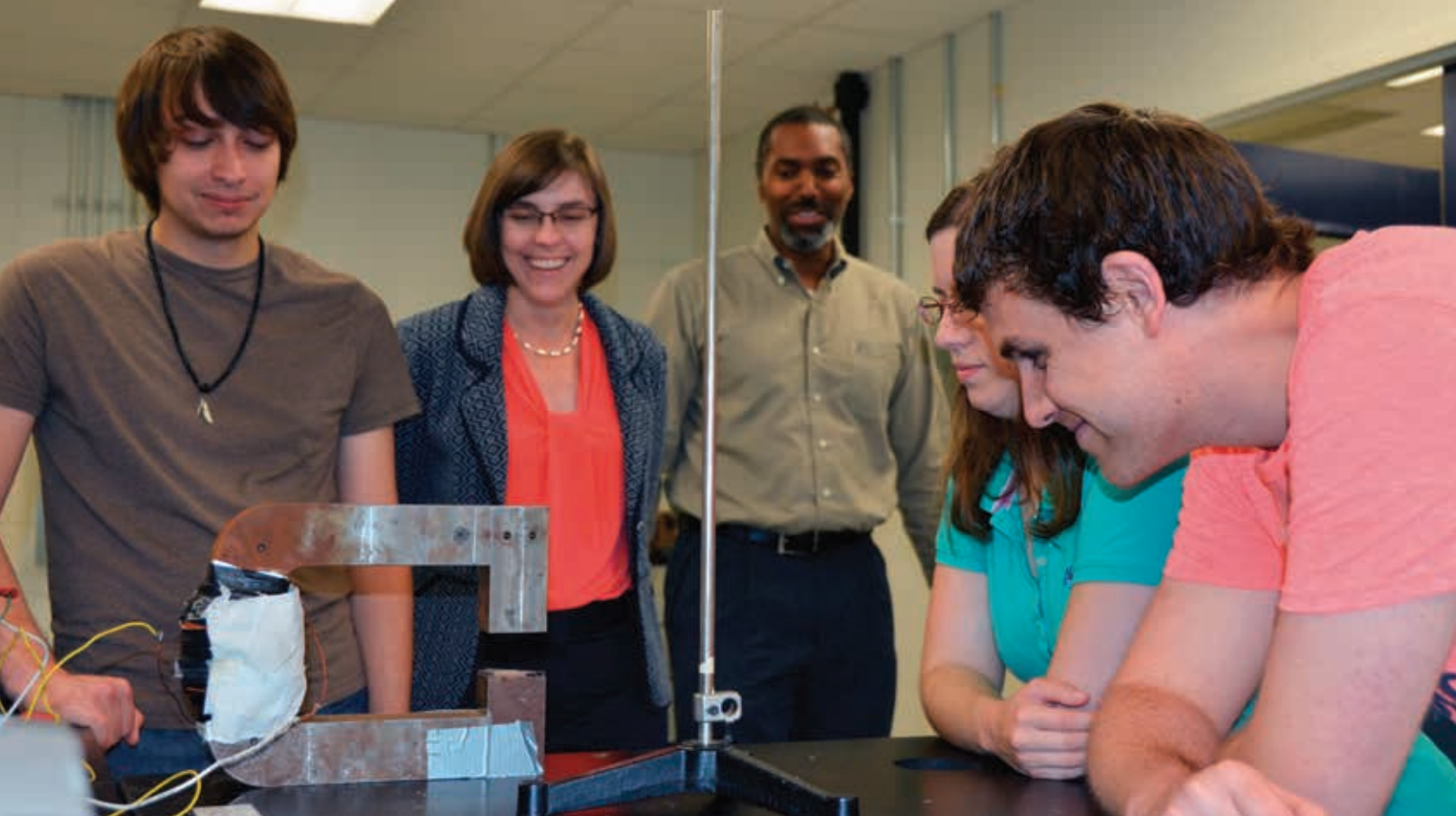
Visit the Wong Laboratory for Nature Inspired Engineering at <http://www.mne.psu.edu/wong/>

Smart Materials

FOLD INTO ORIGAMI SHAPES

The field of smart or active materials includes a wide range of materials that react to some kind of outside stimulus and respond in a useful way. This might involve sensors that respond to temperature changes or the presence of a gas, piezoelectric materials that turn electrical current into mechanical motion and vice versa for energy harvesting or ultrasound, shape memory alloys, or the kinds of materials that fold or unfold as a result of an electric or magnetic field.





Part of the origami team in the von Lockette lab preparing to activate a magnetic elastomeric structure. From left: Brett Cowan (graduate student), Mary Frecker, Paris von Lockette, Katherine Leshkow (graduate student), and Landen Bowen (Ph.D. candidate)

Scott Phillips and his group in Chemistry work on stimuli-responsive materials, called autonomous plastics, for shape-shifting and smart biomedical materials, among other applications. Reggie Hamilton's group in Engineering Science and Mechanics study the microstructure and physical behavior of shape memory alloys for actuation, sensing, and dampening applications. Along with Todd Palmer in the Applied Research Lab at Penn State, Hamilton won an NSF grant to study 3D printing with Nitinol powder, the temperature based reversible shape memory and superelastic alloy of nickel and titanium.

Penn State has been a leader in the piezoelectric and ultrasound area of smart materials for several decades and continues to actively engage in research involving piezoelectric materials. The group led by Susan Trolier-McKinstry has developed a piezoelectric thin film on glass for adjusting the mirror for an x-ray space telescope while in orbit (see "Undergraduate Summer Researcher

Contributes to Futuristic Space Mirror" in this issue), and, with IBM, is developing a high-speed, low-power piezoelectronic switch/transistor that is theoretically capable of functioning at higher speeds than current CMOS technology at 1/100 the power. As part of a collaboration with North Carolina State University, the McKinstry group is developing technologies to harvest energy from the human body to power wearable sensors. Qiming Zhang, Distinguished professor of electrical engineering, is a world leader in electroactive polymers, an active area of smart materials and systems research.

Technically advanced origami

The concept of developing origami principals for technical purposes has been used to pack large-area solar sails, solar arrays, and in the future foldable space telescopes into the narrow confines of launch vehicles. Foldable antennas and foldable batteries have also been demonstrated using well known origami folding techniques.

In 2012, the National Science Foundation's EFRI program, which stands for Emerging Frontiers in Research and Innovation, put out a call for proposals for a new program on origami engineering.

A team led by Mary Frecker, professor of mechanical engineering, was awarded one of the eight grants, which collectively have a goal of learning to design complex systems in fundamentally new ways. The award of \$2 million over four years is co-funded by NSF and the Air Force Office of Scientific Research.

"One of the unique things about this topic, is that it is the first NSF program to require that an artist be part of the grant team," Frecker said. "The idea was that paper folding has been around for centuries and there is a community of origami artists who do amazing and

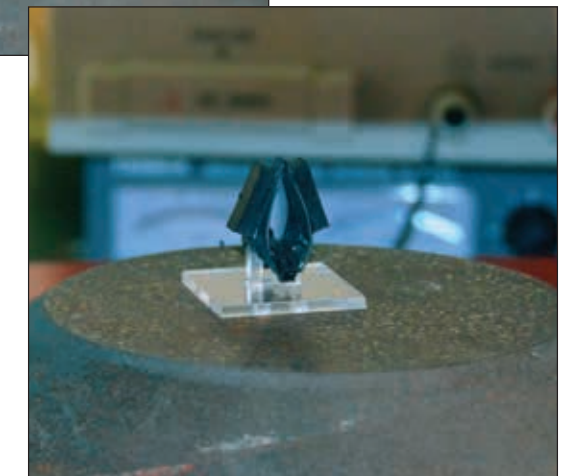
beautiful origami sculptures using paper. There is also a whole community of origami mathematicians who use geometric modeling techniques to predict which three dimensional shapes are foldable."

In addition to Frecker, the team is composed of Rebecca Strzelec, professor of visual arts at Penn State Altoona, who uses computer aided design to make intricate pieces of wearable art; Jyh-Ming Lien, an assistant professor of computer science at George Mason University who develops algorithms to represent geometric data related to shape and motion; Zoubeida Ounaies, associate professor of mechanical engineering at Penn State, whose group is studying electrically activated smart materials; and Paris von Lockette, associate professor of mechanical engineering at Penn State, who works with magnetically active materials. Tim Simpson, professor of mechanical engineering, along with Frecker, focuses on engineering design with interests in 3D printing.

Origami artists use a single sheet of paper to make complex shapes. Although paper is useful as proof-of-concept, for this group's purposes paper is not really



Compliant magnetic materials are activated under an electromagnet in the von Lockette lab to make flapping wings.



considered an engineering material, Frecker said. "In our program, we want to move beyond paper."

Researchers in the field of engineered origami materials are interested in self-folding materials and how to fold a shape without having any self-intersections – meaning panels colliding with each other. Think of a flower opening its petals at sunrise and closing them neatly at sunset. One way to make a flat sheet self fold is by infusing it with some kind of active material, which is the approach that von Lockette and Ounaies are taking.

Compliant magnetic materials – The von Lockette lab

Compliant materials have the ability to elastically deform in response to an outside force without losing their structure or functionality. Paris von Lockette gives his recipe for making a compliant magnetic material: Start with a rubbery base material, a silicone

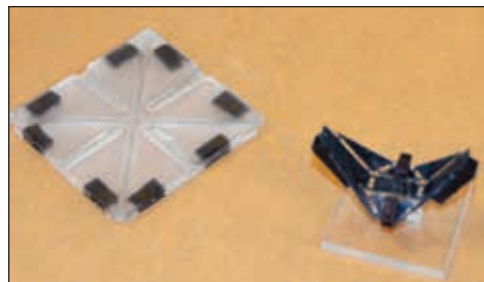
elastomer called polydimethyl siloxane (pdms), in a liquid state and add magnetic particles, such as barium hexaferrite. Mix well and while the compound is curing, put the material in a magnetic field. All the little particles will line up in the direction of the field. Once cured, you will have a rubber material with its own north and south poles.

“We’re one of the first groups to look at adding hard magnetic particles that have north and south poles to these materials,” von Lockette noted. Adding soft magnetic materials, such as iron, has been studied for decades, but under a magnetic field the material just lies there. His materials get up and walk around, or at least that’s the plan. By oscillating the magnetic field back and forth, his material can be made to move in a stepwise fashion. Since the silicone rubber that he uses as a base material is also widely used in MEMS devices, he is looking into the possibility of miniaturizing his walking structures to the point where they could be used to transport payloads on a microchip. By making microstructures that swim in a controlled environment, possibly for drug delivery, or to make self-cleaning devices that can be actuated by a magnetic field, for instance in hydraulic systems that now have to be taken out of service and dismantled for periodic cleaning. “There are a lot of in situ applications that if you put the device in to start you can actuate and you don’t have to take them apart,” he said.

Electroactive materials – The Ounaies Lab

The Ounaies lab focuses on creating new, smart composite materials that combine electrical, mechanical, and electromechanical properties for a variety of uses

in the aeronautic, automotive, medical, and consumer sectors, including electric-field activated origami engineering. Many of the materials her group makes are nanocomposites composed of structurally engineered nanotubes and nanofibers in polymer. For the EFRI project, they are developing multi-field active materials made of electroactive polymers.



Magnetically activated elastomers are used for folding or flapping structures.



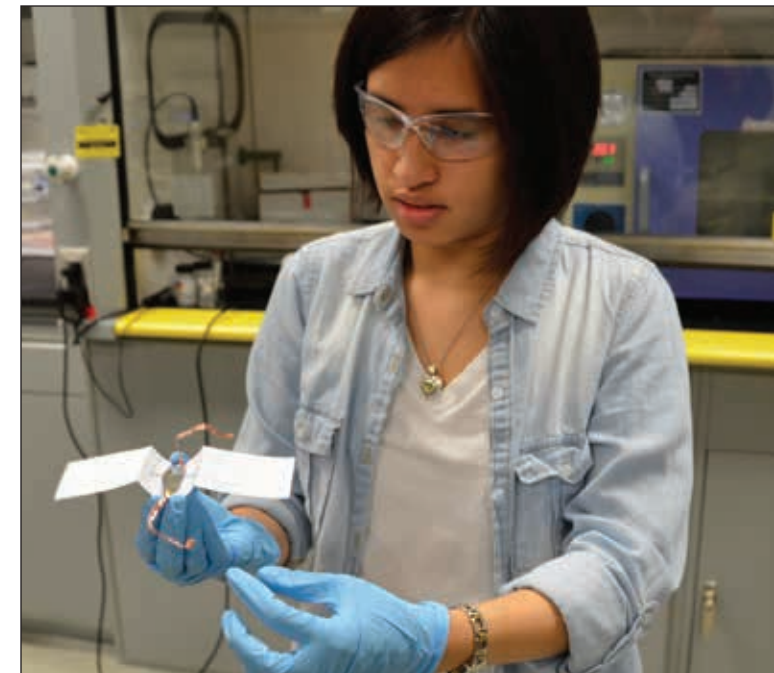
Magnetically activated wings

On a recent visit to the Ounaies lab, I found her students applying smart materials to paper in order to fold them into three-dimensional shapes for demonstration purposes.

“In a broad sense, we are making origami structures,” said Saad Ahmed, a Ph.D. student in Ounaies research group. “Applying an external force, either an electric or a magnetic field or heat, to a smart material, and the smart material will turn into any type of 3D object, a self-folding origami structure.”

Erika Arrojado, an undergraduate working in the Ounaies lab, took up the story from there. “The active material we are using is an electroactive polymer called a terpolymer. I apply a small amount of the terpolymer film to areas of the structure, in this case paper. When I apply an electric field to the film it causes the paper to fold. The three structures I’m working on are called the flapping bird, the catapult, and the barking dog.”

The catapult has proven to be especially popular at science fairs and conferences. “We have two strips of terpolymer film that are each eight layers thick,” Arrojado said, preparing to demonstrate the catapult. “I’ve sputtered silver electrodes on each film and attached copper wire electrodes that I’ll attach to the leads. If you manually activate it by pulling the tabs, it will launch a projectile. But instead we have the electric field activate it, like this.”



Arrojado with mentor and Ph.D. candidate Saad Ahmed

Undergraduate researcher Erika Arrojado demonstrates an electroactivated terpolymer on paper wings in the Ounaies lab.

At a recent American Society of Mechanical Engineers (ASME) conference on smart materials, Ounaies and Frecker got the participants involved in a paper catapult building activity they had developed for high school students. “Everyone followed their instructions and folded their catapults. We lined them up and launched them, and gave the winner a prize. It was so much fun, and not something you would typically do at a conference,” Frecker said.

Mentoring – An important piece of the project

“This origami project is the best project I’ve ever worked on,” Frecker enthused. “We have a great group of collaborators and there is so much interest in origami I never knew about.”

An important piece of the project, said Frecker, was an add-on to the grant called REM, for Research Experience in Mentoring. This supplement from NSF allowed her to bring onboard three undergraduate students and a high school teacher, Kelly Forest, a physics teacher at the Grier School, a private girls boarding school in nearby Blair County. Forest was able to add origami materials to her classroom curriculum. In addition, two students from State College High

School, Sarah Dangelo and Hannah Feldstein, gained valuable experience as members of the team.

The REM students developed remote control cars with an active origami tower on each car. As the cars drive through an obstacle course, the height of the towers adjusted to hit or avoid targets. Over the summer, the students took origami projects to the Discovery Space Museum in State College to introduce six to eight year old girls to STEAM –science, technology, engineering, arts, and math topics. A similar program was put on at the Palmer Museum of Art on campus for young boys and girls. An origami teaching module was created for the volunteer engineering students group, Engineering Ambassadors, to take to local middle and high schools where they interact with some 2000 students each year.

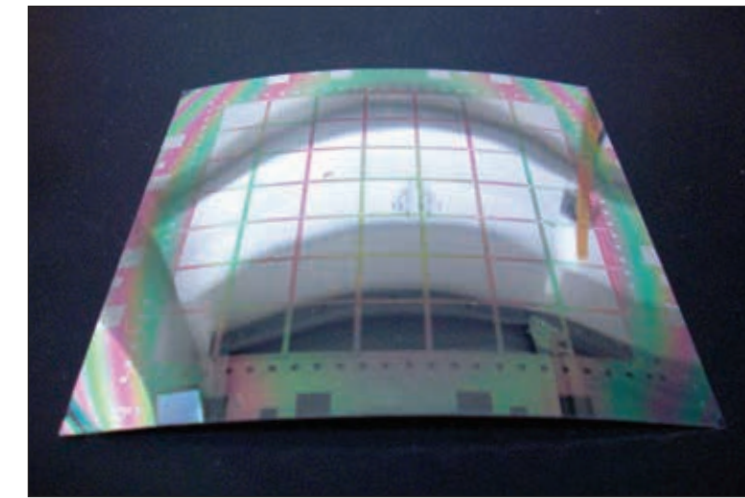
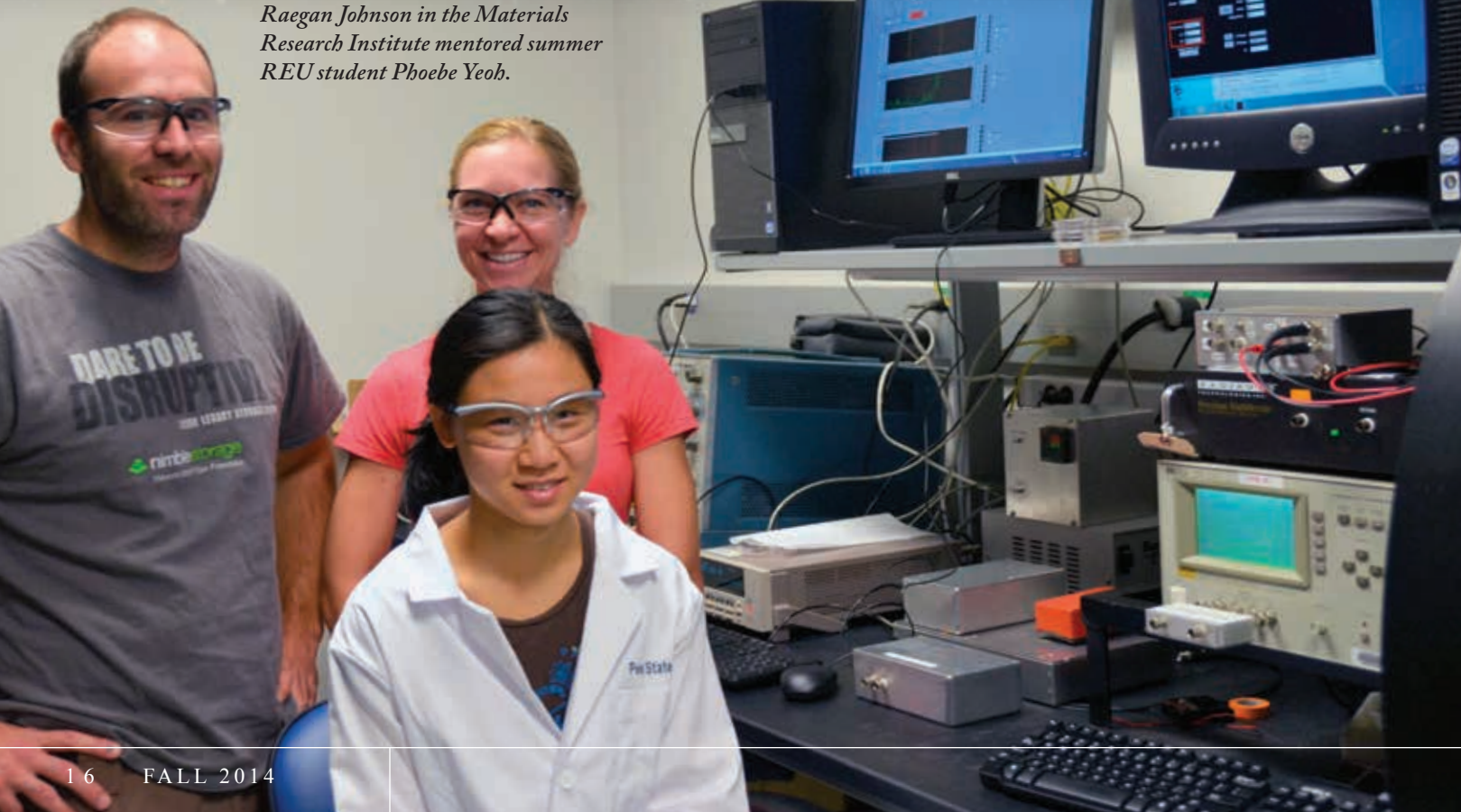
“I’ve never had high school students working in my lab, and they were just fantastic,” Frecker said. “They got along well with the students in my lab, and they got to see what it is like to do research at a graduate level. I view the REM project as being just as important as the research.”

Mary Frecker can be contacted at mx36@psu.edu. Paris von Lockette can be contacted at prv2@psu.edu.

UNDERGRADUATE SUMMER RESEARCHER CONTRIBUTES TO FUTURISTIC SPACE MIRROR

Phoebe Yeoh is a rising senior at Goucher College in Baltimore. A physics major with a minor in math, Phoebe wants to go to a large research university with an established program in materials science and engineering after she graduates. Penn State is one of her possibilities.

Staff scientists Derek Wilke and Raegan Johnson in the Materials Research Institute mentored summer REU student Phoebe Yeoh.



A section of an adjustable lightweight mirror for a space-based X-ray telescope Credit: Penn State

This summer, Phoebe spent ten weeks finding out what it would be like to work in a large research group like that of Professor Susan Trolier-McKinstry's on a project that may someday take her research into space.

"I chose Penn State because I wanted to see the resources a really huge school has to offer," Phoebe explained near the end of her summer experience. "Goucher is a small Liberal Arts college with a small physics department. I couldn't really get a materials background there."

Phoebe was immediately immersed in an ongoing project to develop an adjustable mirror for the proposed SMART-X mission, the goal of which is to build a space-based X-ray telescope that will greatly expand the map of the universe. Phoebe worked on depositing thin films of a piezoelectric material to curved glass substrates. When an electric field is applied, the piezoelectric material will change its shape, bending the glass slightly to improve the focus of the telescope. The proposed space mirror will give the telescope 30 times the effective light capturing area of the current Chandra X-ray telescope without sacrificing on angular resolution.

"The current X-ray telescope is huge and the mirrors are super bulky. I've been working with mirrors that are 400 microns thick, so we could get a telescope with equal or better resolution that is also much lighter and thus less expensive to launch into space," she explained.

Working with two Ph.D. mentors in the McKinstry group, research associates Derek Wilke and Raegan Johnson, Phoebe learned to deposit lead zirconate titanate (PZT) on glass in the cleanroom of the

Nanofabrication Laboratory using a RF magnetron sputtering system.

"I spend half my time or more in the cleanroom," Phoebe said. "I've enjoyed it a lot. The cleanroom staff who trained me were really nice. I've basically learned more lab techniques this summer than I have in the last three years."

Raegan Johnson explained Phoebe's contribution to their research. "There are a number of electrodes on top of the PZT that are about one centimeter square. That's relatively large size for electrodes, so we tend to see

a lot of shorting. We've spent several years trying to get better quality PZT to minimize shorts, but we have not had success with high yield on curved surfaces. The film that Phoebe deposited this summer on a curved piece gave us 100% yield. Given this success, we would love if she returned as a grad student!"

The REU experience culminates in a university-wide poster

session describing some aspect of the student's summer research project. Phoebe focused on optimizing the deposition parameters of the 1.5 micron-thick PZT film on curved glass, and testing the electrical and electromechanical properties of the film. Her successful growth of perovskite phase films with 100% yield for cm² electrodes on curved glass brings the team's goal of putting a new X-ray telescope in space a big step closer.

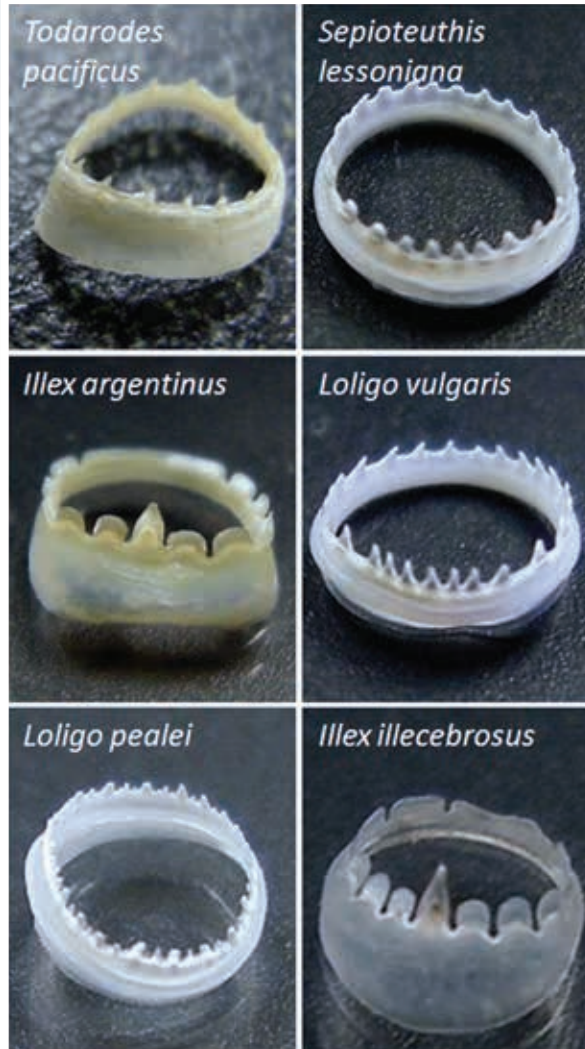
The Penn State Physics Department/Center for Nanoscale Science REU program is supported by the Physics Department and the National Science Foundation. Susan Trolier-McKinstry, professor of materials science and engineering and co-director of the Nanofabrication Laboratory, can be contacted at set1@psu.edu.



A thermoplastic made of squid protein can be stretched up to 300%.

A RENEWABLE BIOPLASTIC MADE FROM SQUID PROTEINS

In the central Northern Pacific is an area that may be the size of Texas called the Great Pacific Garbage Patch. Made up of tons of floating plastic debris, the patch is killing seabirds and poisoning marine life in the North Pacific Ocean and in other oceans where converging currents, called gyres, concentrate the floating plastic. Over time, plastic bottles and fishing lines from coastal locations and seagoing vessels break down into nearly invisible pieces small enough to enter the food chain where some of the chemicals may eventually be ingested by human beings.



Squid ring teeth proteins can be mixed across species to engineer the required properties.

At Penn State, a group led by Melik Demirel, professor of engineering science and mechanics, is designing a biodegradable plastic from structural proteins that could help clean up the world's oceans and solve an interesting set of other problems along the way.

Demirel and his students have gathered squids from around the world, from the Atlantic coast, the coast of Spain, from Korea, and later this year, from Argentina. From these specimens, his lab has extracted the squid ring teeth (SRT) from their tentacles, and re-engineered their proteins in ways that go beyond nature. He plans to find ways to biosynthesize the engineered protein in bacteria through fermentation on an industrial scale. And though that may be a few years down the road, it is entirely feasible, he believes.

"Structural proteins are eco-friendly materials with remarkable mechanical properties," he says. "It's a material that looks a lot like silk, except that it is thermoplastic, which means that it can be melted and reshaped into different forms without losing its properties. Like silk, SRT is lightweight and strong, which is why the Army is interested in the material for textiles."

The convergence of materials and life sciences

In the Demirel lab, graduate student Abdon Pena-Francesch removes the protein from the suction cups on the squid's tentacle using a toothpick. He then processes the protein into a viscous melt at a temperature above its softening temperature, around body temperature in water. The melt could be used in a number of industrial processes, such as electrospinning, extrusion, molding, or by coating onto a surface. A new and potentially dramatic way to use the protein melt is in 3D printing.



Melik Demirel, professor of engineering science and mechanics, is designing thermoplastics from squid ring teeth proteins.

"The squid protein Abdon is working with can be melted and solidified over and over without losing its mechanical properties, which include high toughness (how much energy it can absorb), high strength (the load that can be borne before failure, around one gigapascal), and its extensibility (how far can it be stretched before breaking), which can be engineered up to 300%," Demirel says. In addition, this fibrous protein can be chemically functionalized and can be controlled so as to biodegrade in anywhere from hours to years. This makes squid protein a good prospect for packaging, such as plastic bottles, or timed-release drug delivery.

With so many potential advantages to using a safe, recyclable, biodegradable, composite material, there is still a big roadblock, says Demirel. That is the processing of the tiny rings is slow and expensive and there are not enough squids in the ocean for an industrial scale material. In order to compete with plastics that are a byproduct of relatively cheap oil extraction, a better method for producing these proteins is required.

This is where materials science and life sciences begin to converge, Demirel says. Genes coding squid proteins were read by sequencing instruments in the Genomics Facility at Penn State. Once Demirel's team obtained the genomic data, they had to find out which portions of the data actually contain the code for protein formation. For this they took their data to the Proteomics and Mass Spectrometry Facility at Penn State. Both facilities are operated by the Huck Institutes of the Life Sciences.

"At the Proteomics Facility, we read the sequence of the protein. The problem is the mass spectrometer can only read a small portion of the sequence at a time. That's when bioinformatics people step in, such as Dr. Istvan Albert and his Bioinformatics Consulting Center in

the Dept. of Biochemistry and Molecular Biology,” Demirel says. “They start building the whole map, put it into bacteria and express it.”

There are multiple systems for biologically synthesizing the squid proteins into a plant or animal system.



Graduate student Abdon Pena-Francesch heats a sample of self-healing plastic made from squid ring teeth in the Demirel lab.

These include bacteria, yeast, mammal, plant, or insect systems. Demirel currently works with Wayne Curtis, professor of chemical engineering, to express the protein in bacteria. Bacteria are already in use to make high-end products such as pharmaceuticals and cosmetics.

There are several proteins in squid tentacles, some of which show thermoplastic properties and others elastic properties. The ratio of these proteins is distributed differently in each of the species. This gives his group a large canvas of properties to work with.

“Now we can go beyond nature, because we can take each of these proteins and mix them as we wish. We can mix within species or we can mix across species. We know by theory that depending on their molecular weight they will either be all thermoplastic or all thermoelastic. By mixing the molecular weight you get something in between,” says Demirel.

His group is already producing on the order of 100s of grams of protein. Their goal is to produce kilograms by the end of this year, and then, in the next couple of years, tons. Eventually with Wayne Curtis’ expertise, he proposes to make a thermoplastic elastomer that is competitive with synthetic oil-based plastic.

In the lab, Pena-Francesch coats a glass slide with a squid protein and sets a second glass slide on top of it. The two slides bond, and it takes a powerful pressure to pull them apart. The adhesive is stable underwater for at least six months and could be used for a marine coating or for bandages for wound healing. The fibrous protein can be reformed several times and retains its elasticity or stiffness in wet or dry conditions.

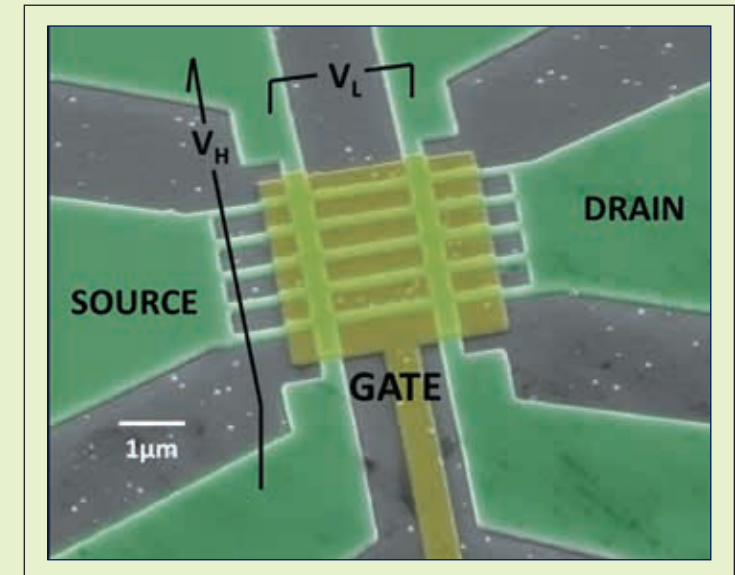
Next, he stretches a small strand of elastomer protein with small pliers until it finally snaps. To demonstrate the material’s self-healing property, Pena-Francesch heats the broken strands above its softening temperature and rejoins the ends seamlessly.

“We are in the process of taking something from nature, reproducing it, and mimicking it using gene sequences to get properties that materials scientists are interested in, such as specific physical properties including surface, mechanical, and barrier properties,” Demirel says.

Contact Prof. Demirel at mdemirel@engr.psu.edu

In the consumer electronics industry, the mantra for innovation is higher device performance/less power. Arun Thathachary, a Ph.D. student in Penn State’s Electrical Engineering Department, spends his days and sometimes nights in the cleanroom of the Materials Research Institute’s Nanofabrication Laboratory trying to make innovative transistor devices out of materials other than the standard semiconductor silicon that will allow higher performance using less power.

Materials Other Than Silicon for Next Generation Electronic Devices



Scanning Electron Microscope micrograph of multigate InGaAs nanowire field effect transistor with an array of five nanowires of width 40 nm. Credit: Arun Thathachary, Penn State

Silicon has been the most successful material of the 20th century, with major global industries and even a valley named after it. But silicon may be running out of steam for high performance/low power electronics. For example, the compound semiconductor indium gallium arsenide is known to have far superior electron mobility than silicon. As silicon strains against the physical limits of performance, could a material like InGaAs provide enough of an improvement over silicon that it would be worth the expense in new equipment lines and training to make the switch worthwhile? Samsung, one of the world’s largest electronics companies, has

funded Thathachary through his adviser, professor of electrical engineering Suman Datta, in a project to help them find out.

In an article in the journal *Nano Letters* early this year, Thathachary and his coauthors described a novel device prototype designed to test nanowires made of compound semiconductors such as InGaAs. Their goal was to see for the first time if such a compound material would retain its superior electron mobility at nanoscale dimensions in a so-called FinFET device configuration, the standard transistor architecture for sub-22 nanometer technology.

“We developed a novel test structure called a Multi-fin Hall Bar Structure. It is the first such measurement of Hall mobility in a multi-fin 3D device,” Thathachary said. “If you look at mainstream chip production today, all transistors are made in a 3D fashion, and because they are made in 3D rather than the earlier planar design, several mechanisms can degrade performance. What we looked at in that paper is how much degradation do you really suffer when going from a planar 2D surface to, in this case, 30 nm size features that are confined in 3D?”

What Thathachary and colleagues discovered was that electron mobility declined in a regular slope and that the experimental results could be modeled by a method called scattering relaxation time approximation. Using this technique they were able to predict how a compound semiconductor device would be likely to operate at the size at which this material would possibly be adopted, for example, the 7 nm technology node.

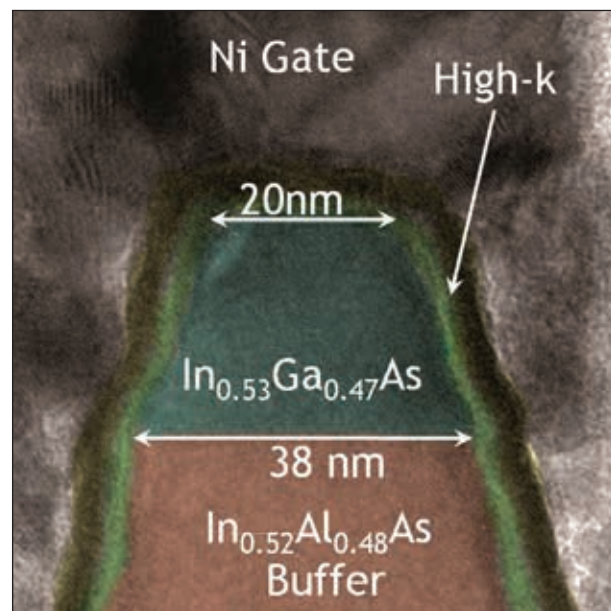
“We found that at dimensions of even 5 nm, you can still expect a 2x to 3x advantage in the mobility of these materials over silicon, which is very significant,” said Thathachary. “After we published this paper, it was clear from a fundamental physics point of view that if you engineer the device correctly you should outperform existing silicon devices. But will it really? That’s what we set out to investigate next.”

Conference paper draws interest

The VLSI Symposia is an international conference on semiconductor technology and circuits, the leading conference for discussing advances in microelectronic devices. The majority of the presenters are from

industry, with only a handful of student papers picked for presentation. At this year’s VLSI, one of the papers was Thathachary’s.

“The paper in *Nano Letters* was a precursor to the one chosen for the conference,” Thathachary said. They had made a device with 30 nm features and measured the compound semiconductor’s electron mobility down to that scale, but now it was time to actually make nanoscale transistors out of the new materials system and understand transistor behavior in that system.



Transmission Electron Microscope micrograph of a 20 nm InGaAs finFET device
Credit: Arun Thathachary, Penn State

Two of the parameters that are most important in transistor technology are called “subthreshold slope” and the “on current.” Subthreshold slope indicates how efficiently you can turn the transistor on and off. While on current simply means how much current you can get out of the device. Especially for mobile devices, if the transistor can get the same amount of current with lower voltage it will extend battery life and reduce the amount of heat that has to be gotten rid of.

“In addition, it’s imperative that you increase the functionality of the computer chip,” Thathachary explained, “but that means putting more transistors inside. If you are going to put a 50 or 60 watt limit on the average power consumption of your chip, then those transistors have to require lower power than the existing devices.”

Working on his Ph.D. project and through regular consultation with the Penn State Nanofab engineering staff, Thathachary spent a year in the cleanroom optimizing the processes required to put a new material

system into a state of the art 3D FinFET device. That required spending many hours tweaking the conditions, such as temperature, flow rate, types of reactant gases, as well as refining his electron beam lithography and dry etch patterning techniques.

One of the most challenging issues he overcame was etching InGaAs into dense fin arrays comprising nanoscale dimensions. Once that was accomplished, he then needed to see how the new compound semiconductor system interacted with the other materials systems, such as the high-k dielectric thin film coating that surrounded the InGaAs fin.

“If you can get that process right, then you can make a great device, and that is what we showed at the conference,” he said. “We showed that in terms of on current at lower supply voltage we are seeing very good performance compared to existing silicon devices.”

Between the time the conference paper was accepted and the June meeting in Hawaii, Thathachary had continued to refine his processes. He learned that increasing the percentage of indium in the ternary (3-part) material system increased electron mobility significantly. Another mobility boost comes from engineering the dimensions of the active material so that the electrons are forced toward the middle of the material in a process called quantum confinement. This is important because in traditional transistors the electrons move close to the surface where they are exposed to microscopic roughness that degrades their mobility.

“The paper was remarkably well received at the conference, and we had a lot of requests to share our new and improved results. We had to get permission from Samsung to share that material, and eventually we did,” Thathachary said.

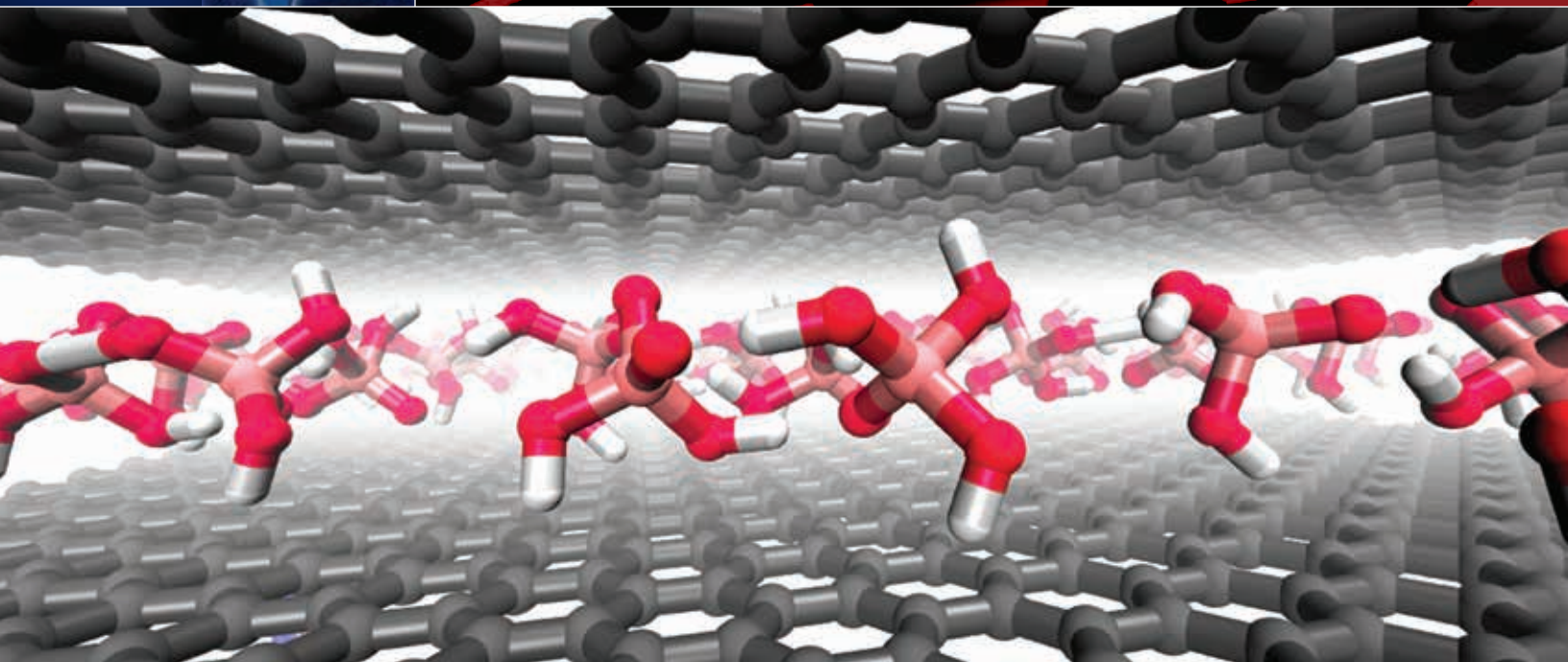
Encouraged by his results, Samsung has since renewed the contract with the Datta lab and Thathachary for another year. His next challenge will be the most difficult so far. They want him to investigate the performance of a 3D transistor at the 7 nm dimension, a node that the semiconductor industry

is looking at for the future. To do this in the Penn State Nanofab for the first time, means he will need to develop innovative ideas to overcome the limitations of working with limited resources in a university lab. Once a device can be made at or approaching those dimensions, Samsung will likely internalize the research and assign a large team of engineers to develop reproducible industry scale devices.

“If we can show that at those dimensions, these III-V compound semiconductor systems can still beat silicon, that is when it makes sense for industry to move in and invest the billions of dollars required for the new technology generation,” Thathachary concluded.

In addition to his adviser, Prof. Suman Datta, Thathachary would like to acknowledge the extensive support of his colleague and labmate Ms. Nidhi Agrawal, who did many of the measurements for the VLSI conference, and the entire staff of the Penn State Nanofab for their support.

Thathachary can be contacted at avt114@psu.edu. Prof. Datta can be contacted at sdatta@engr.psu.edu.



Rethinking the Basic Science of GRAPHENE SYNTHESIS

A model of the intercalation of Brønsted acid molecules between single-atomic layers of graphene. Credit: Mallouk Lab, Penn State University

A new route to making graphene has been discovered that could make the 21st century's wonder material easier to ramp up to industrial scale. Graphene – a tightly bound single layer of carbon atoms with super strength and the ability to conduct heat and electricity better than any other known material – has potential industrial uses that include flexible electronic displays, high-speed computing, stronger wind turbine blades, and more efficient solar cells, to name just a few under development.

In the decade since Nobel laureates Konstantin Novoselov and Andre Geim proved the remarkable electronic and mechanical properties of graphene, researchers have been hard at work to develop methods of producing pristine samples of the material on a scale with industrial potential. Now, a team of Penn State scientists has discovered a route to making single layer graphene that has been overlooked for more than 150 years.

“There are lots of layered materials similar to graphene with interesting properties, but until now we didn’t know how to chemically pull the solids apart to make single sheets without damaging

the layers,” said Thomas E. Mallouk, Evan Pugh Professor of Chemistry, Physics, and Biochemistry and Molecular Biology at Penn State. In a paper first published online Sept. 9 in the journal *Nature Chemistry*, Mallouk and colleagues at Penn State and the Research Center for Exotic Nanocarbons at Shinshu University, Japan, describe a method called intercalation, in which guest molecules or ions are inserted between the carbon layers of graphite to pull the single sheets apart.

The intercalation of graphite was achieved in 1841, but always with a strong oxidizing or reducing agent that damaged the desirable properties of the material.

One of the mostly widely used methods to intercalate graphite by oxidation was developed in 1999 by Nina Kovtyukhova, a research associate in Mallouk’s lab.

While studying other layered materials, Mallouk asked Kovtyukhova to use her method, which requires a strong oxidizing agent and a mixture of acids, to open up single layers of solid boron nitride, a compound with a structure similar to graphene. To their surprise, she was able to get all of the layers to open up. In subsequent control experiments, Kovtyukhova tried leaving out various agents and found that the oxidizing agent wasn’t necessary for the reaction to take place.

Mallouk asked her to try a similar experiment without the oxidizing agent on graphite, but aware of the extensive literature saying that the oxidizing agent was required, Kovtyukhova balked.

“I kept asking her to try it and she kept saying no,” Mallouk said. “Finally, we made a bet, and to make it interesting I gave her odds. If the reaction didn’t work I would owe her \$100, and if it did she would owe me \$10. I have the ten dollar bill on my wall with a nice Post-it note from Nina complimenting my chemical intuition.”

Mallouk believes the results of this new understanding of intercalation in boron nitride and graphene could apply to many other layered materials of interest to researchers in the Penn State Center for Two-Dimensional and Layered Materials who are investigating what are referred to as “Materials Beyond Graphene.” The next step for Mallouk and colleagues will be to figure out how to speed the reaction up in order to scale up production.

Their results appear in the *Nature Chemistry* article titled “Non-oxidative intercalation and exfoliation of graphite by Brønsted acids” (<http://dx.doi.org/10.1038/nchem.2054>) by Nina I. Kovtyukhova, Yuanxi Wang, Ayse Berkdemir, Mauricio Terrones, Vincent H. Crespi and Thomas E. Mallouk, all of Penn State, and Rodolfo Cruz-Silva of the Research Center for Exotic Nanocarbons, Shinshu University, Nagano, Japan. Their work was supported by the U.S. Army Research Office MURI grant W911NF-11-1-0362.

Contact Prof. Mallouk at tom@chem.psu.edu.



About the Center for Two Dimensional and Layered Materials at Penn State

2DLM

The 2DLM Center conducts multidisciplinary research in the fast emerging field of atomically thin layered materials. Based in Penn State’s Materials Research Institute, the Center works with industry partners, national labs, and academic collaborators to discover and predict new properties that arise when novel materials are created one atomic layer at a time.

Visit the website at <http://www.mri.psu.edu/centers/2dlm/>.

FACULTY SPOTLIGHT

ALLISON BEESE

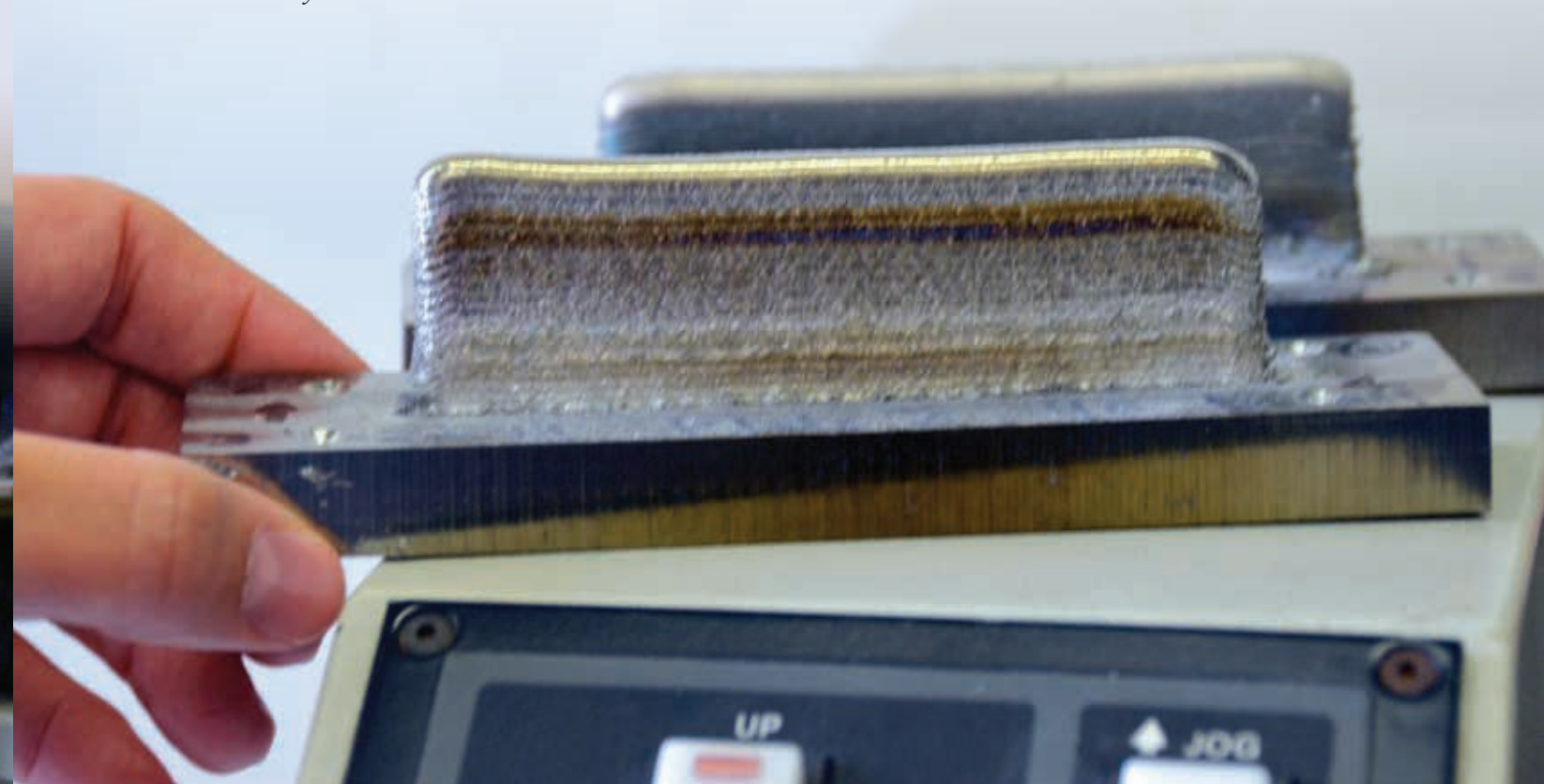
A Lot Still to Learn About

STEEL



Allison Beese, MacFarlane assistant professor of materials science and engineering, is an expert in the study of advanced high strength steel.

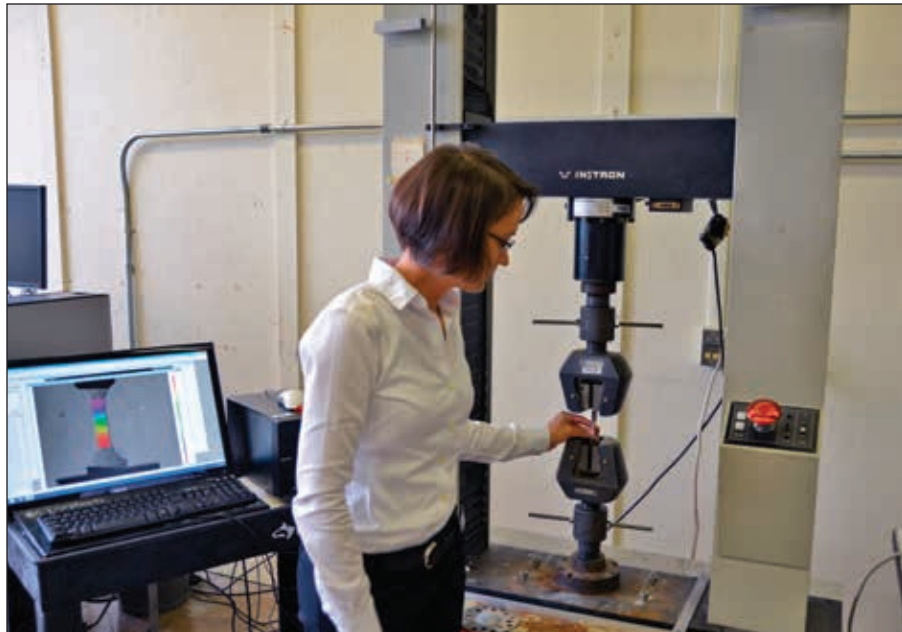
Additively manufactured samples (walls) of nickel superalloy (Inconel 625) and a titanium alloy (Ti-6Al-4V) are being tested by Beese and her students.



Steel is one of the most common structural materials, truly one of the foundations of modern civilization. Steel, an alloy of iron and carbon, has been made since biblical times, and Damascus steel was famous for its strength in knife and sword blades throughout the ancient world. Recently, a team of scientists in Germany discovered that the reason for its unusual ability to hold a sharp edge may have been from carbon nanotubes and nanowires that formed in the steel during processing.

With two thousand years of experience in steelmaking, it would seem all there is to know about steel would already be known. For Allison Beese, McFarlane Assistant Professor in Materials Science and Engineering, the secret world of steel is still unfolding.

“There is a lot known about traditional steels, but advanced high strength steels are a different story,” Beese explains. “For example, traditional fracture models don’t accurately predict the properties of these advanced steels. We’re still trying to understand the mechanisms for damage accumulation and fracture, and steel companies are very interested in developing other designs for steel.”



Prof. Allison Beese, prepares to stretch a sample of advanced high strength steel (stainless steel 301LN) while a camera and software setup capture deformation.

carbon nanotubes and graphene oxide. She also used transmission electron microscopy to do in situ testing of the mechanical properties of strong but inexpensive carbon nanofibers. At Penn State, Beese is working with Joshua Robinson, assistant professor of materials science and

engineering, to measure the mechanical properties of 2D films his group is synthesizing and characterizing.

“I am primarily an experimentalist in trying to understand the connection between microstructure and macroscopic mechanical behavior. Through the understanding of deformation mechanisms, we can then develop predictive models,” she says.

3D printing of metallic materials

Additive manufacturing, commonly known as 3D printing, is a rapidly growing technology with large implications for industry. However, especially when it comes to printing metallic materials, much remains to be learned. Penn State has been named the metals node for America Makes, the national 3D printing initiative. In the Center for Innovative Materials Processing Through Direct Digital Deposition (CIMP-3D), the resources and experience in lasers and materials of Penn State’s Applied Research Laboratory and Materials Research Institute are focused on developing a basic understanding of layer by layer fabrication in order to build structural components for automotive and aerospace applications, among others. Here, metal is deposited in a desired location, melted with a laser, and then as it solidifies, it fuses to the layer below.

In her temporary lab on the east end of campus where her department has been displaced while Steidle Building undergoes renovations, Beese and her students stretch pieces of high strength stainless steel in a test unit and use digital image correlation to quantify the deformations. A speckled pattern painted on the steel sample with spray paint is captured by a camera in one second intervals while software looks for the same pattern as its shape changes under applied deformation. The best steels have high strength in conjunction with ductility, the ability to be stretched. Alloying small amounts of materials such as manganese can add to steel’s strength, while phase transformations during processing or deformation can change the steel from soft to extremely hard and strong. Most importantly, she studies the effects of microstructure on mechanical properties.

During her postdoctoral work at Northwestern, Beese studied the microstructure of carbon nanotube and graphene oxide composites. Taking insights from tough natural materials, such as mother of pearl, which has both strength and resilience due to its hierarchical microstructure and layers of hard inorganic and elastic organic materials, she and her collaborators designed bioinspired materials using

“Rapid thermal fluctuations as the laser heat source scans over the material one layer at a time will dictate the microstructure of the deposited metal, which in turn will dictate the mechanical properties,” Beese explains. Her group has been testing relatively large components, or walls, of an additively manufactured nickel superalloy (Inconel 625), a stainless steel (304), and a titanium alloy (Ti-6Al-4V). By carving out a smaller sample from the walls, her group can measure mechanical properties as a function of the location and direction of the layers. They have found that ductility is dependent on the direction of the build, while strength varies at different heights. This is a result of differences in the way heat is dissipated, as well as the thermal cycles, as more material is deposited.

“People who directly make small 2D samples for testing are not going to see these differences, which are important since they will show up in large scale structural components,” she points out.

Undergraduate and graduate researchers

Beese has two students working on the 3D project who are funded by the National Science Foundation. She also has half a dozen undergraduates in her lab working on different projects. She sees working with undergraduates as a good way to encourage them to go on to graduate school or as training for working in a group setting in industry.

“It’s rewarding to mentor undergraduate and graduate students individually. It’s especially helpful for undergraduates to have a chance to apply their classroom learning in the lab. My goal with respect to the graduate students is to help them to become independent researchers,” she says.

As an undergraduate student at Penn State, Beese performed research for her honors thesis in the lab of Dominic Santavicca, professor of mechanical engineering.

“He and his group were developing a microengine, and I worked on experimental measurements for a

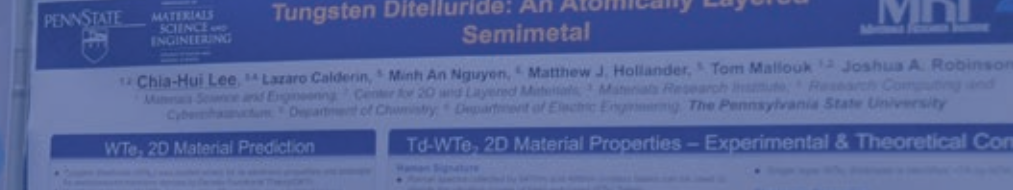
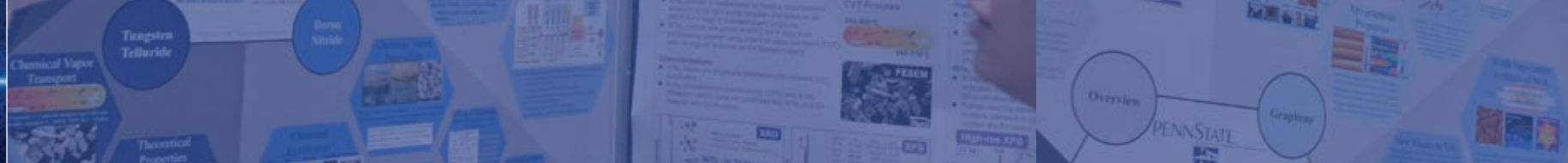
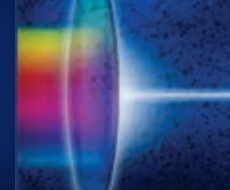
thermal actuator to determine how much of the heat input could be converted to mechanical work, and subsequently, electricity,” she recalls.

After earning her undergraduate degree in mechanical engineering, Beese went into industry at Lockheed Martin’s Knolls Atomic Power Laboratory in upstate New York. She earned her M.S. and her Ph.D. degrees in mechanical engineering with a minor in biomechanics at MIT. As a postdoc at Northwestern, she mentored numerous graduate students, helping them to determine how to accomplish their research goals.

Beese’s twin sister has pursued a similar path and is currently a postdoc in genetics at Harvard. “We are alike in that we are both very science and math-oriented, and we both came to Penn State considering degrees in engineering. However, Sara found that she was very interested in life sciences, whereas I was more drawn to physics. Therefore, she majored in biochemistry and molecular biology and earned her Ph.D. from Johns Hopkins.”

Beese has received a \$300,000 grant from the National Science Foundation in conjunction with Assistant Professor of Materials Science and Engineering and Senior Research Associate Todd Palmer. The award will allow her to conduct fundamental research on additive manufacturing of metallic materials.

Allison Beese is assistant professor of materials science and engineering and Norris B. McFarlane Faculty Professor. She can be contacted at beese@matse.psu.edu.



INDUSTRY AND RESEARCHERS MEET AT MATERIALS DAY

Materials Day is the annual event that brings representatives from some of the top U.S. companies to University Park to meet one-on-one with the students and faculty who are at the forefront of materials research. Held October 7 & 8, 2014, this year's event, with the theme **Materials in Manufacturing**, featured a keynote speech by IBM Fellow **Subramanian S. Iyer**, the engineer responsible for the computer chip that powers **Watson**, IBM's powerful cognitive computing system.

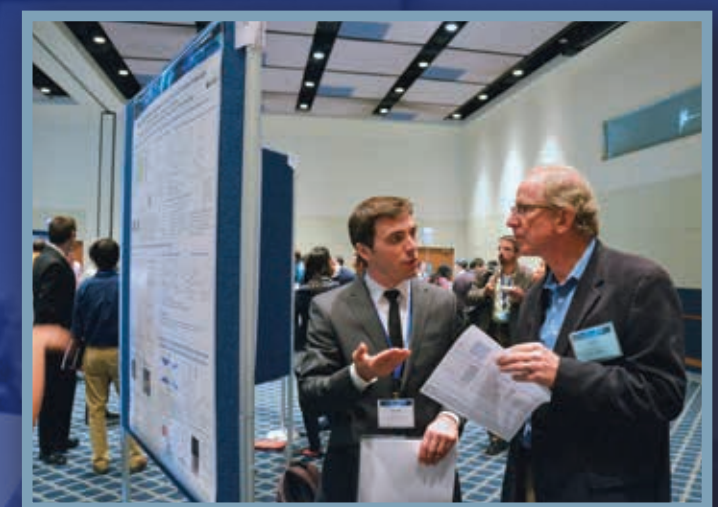
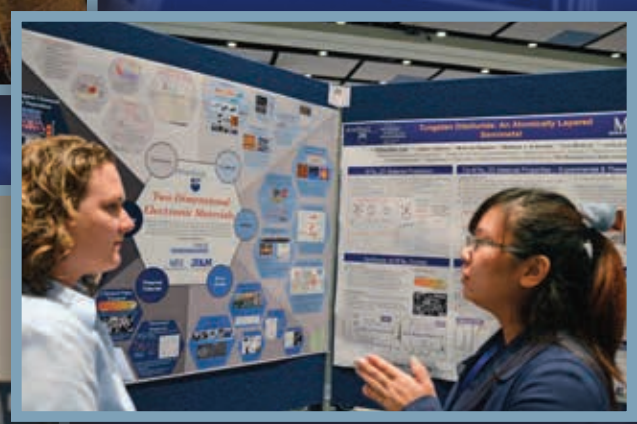
Materials are crucial to solving many of civilization's biggest challenges, from making clean water from polluted sources to storing the sun's energy to making the technological breakthroughs that keep the economy clicking. Industry looks to top research universities like Penn State for the materials science that will underlie the next generation of products. With that thought in mind, Penn State's Materials Research Institute offered industry attendees a choice of technical workshops to highlight the advanced nanofabrication, characterization, computational modeling, and electron microscopy capabilities available at University Park.

directly involved, graduate students, post-docs and technical staff.

Penn State has been a recognized leader in materials research for the past half century with strengths in electronic materials, biomaterials, polymer science, additive manufacturing, and the new field of two-dimensional and layered atomic materials. MRI connects and supports the nearly 250 materials scientists and engineers across five colleges and 18 departments and provides the state-of-the-art facilities and equipment necessary to meet the challenges of the 21st century.

Penn State faculty and invited industry speakers covered topics related to the Materials in Manufacturing theme such as additive manufacturing and 3D printing, energy harvesting and energy storage based on polymers optimized by nanocomposite fillers, the role of simulation in design and manufacturing and the emerging field of atomically thin materials and coatings, and electrically-assisted manufacturing – a technique invented by John Roth at Penn State Erie that can make materials easier to work with and reduce by as much as 90% the power required to form materials.

The Materials Research Institute's acting director, Prof. Clive Randall, spoke on the technology start-ups arising from MRI faculty research – five new companies in the past year – areas of strength and new research directions for MRI. Following his talk, an interactive poster session with over 100 posters allowed industry representatives to discuss the latest research activities with the researchers



PENNSTATE



MRI

MATERIALS RESEARCH INSTITUTE

MRI N-317

Millennium Science Complex
University Park, PA 16802

Nonprofit Org.
U.S. Postage
PAID
State College, PA
Permit No.1

In the Next Issue:

MATERIALS FOR HUMANITY

