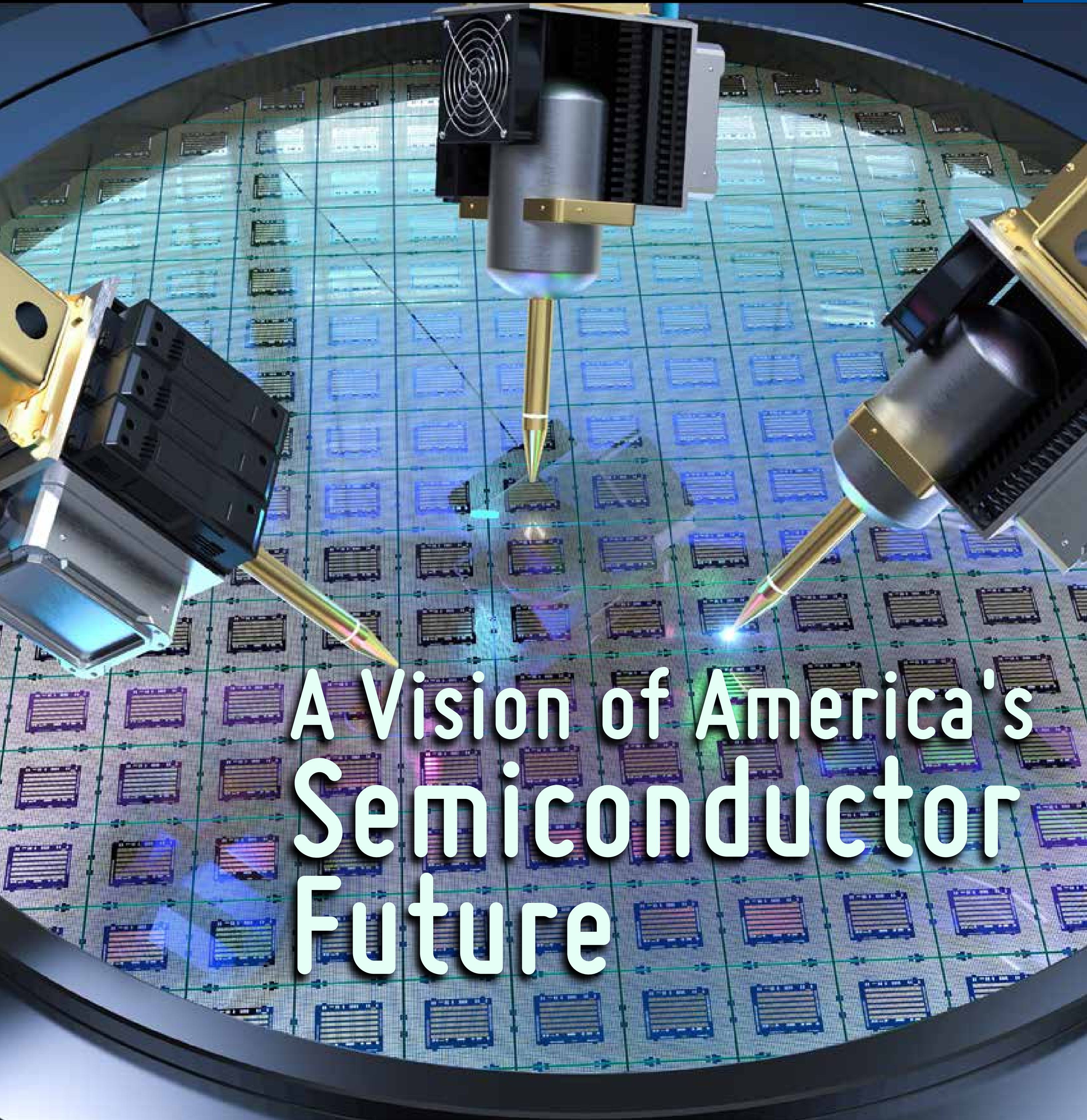
PennState
Materials Research
Institute

FOCUS on MATERIALS

MATERIALS RESEARCH INSTITUTE BULLETIN

FALL 2022



A Vision of America's Semiconductor Future

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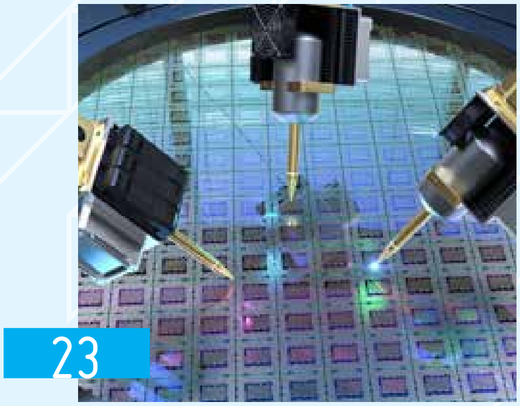

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From the Director

Sometimes you get a strong call to action and must answer it. In the case of the Materials Research Institute (MRI), it was a call to action that we are most certainly prepared to handle: the passing of the CHIPS (Creating Helpful Incentives to Produce Semiconductors) and Science Act, which was signed into law by President Joe Biden on August 9. The CHIPS Act provides billions of dollars for subsidies to American semiconductor manufacturers and for R&D related to emerging semiconductor technologies along with extensive re-imagining of workforce development. Given their ubiquitous and growing presence in our lives in everything from military equipment to the latest phones to sensors to climate-friendly lighting, their importance cannot be understated.

The need for America to up our semiconductor game is clear, as the United States had a 37% market share of semiconductor production in 1990, and today, it is only 12% (as per the Semiconductor Industry Association). Meanwhile, other countries such as China, Taiwan, and South Korea are investing in their semiconductor industry at high levels. It is hard not to see how this is a general call to action for our scientists.

For MRI and Penn State, this is also an opportunity. Penn State was ranked number one in materials science and number two in materials engineering for the fourth consecutive year in the National Science Foundation's HERD national rankings, so our faculty's reputation speaks for itself. We have the R&D know-how, but we view the semiconductor problem, and the solution to it, as a full-spectrum issue that we can contribute greatly to solving.

By full spectrum, I am referring to everything from R&D to manufacturing techniques to workforce development. The diversification of the semiconductor industry demands it, with a clear need for expertise to develop next-generation materials and structures, agile fabrication methods to manufacture the latest breakthrough material, new and increasingly sophisticated packaging solutions, and education for the semiconductor workforce of the future.

These faculty and staff researchers work within a robust research infrastructure. This includes the National Science Foundation-supported national user facility Two-Dimensional Crystal Consortium Materials Innovation Platform (2DCC-MIP), the Nanofabrication Laboratory, the Materials Characterization Laboratory, and the Institute for Computational and Data Sciences. These facilities house state-of-the-art research tools and are fully staffed by a crew of highly qualified, experienced scientists and technicians, processing and characterizing wafers of up to 200 millimeters in our nanofabrication and characterization facilities.

We also actively partner with industry, government agencies, and other educational institutions, especially within Pennsylvania. This includes over 100 companies and 250 independent organizations since 2017 alone. These partnerships are key for our semiconductor workforce development. We offer one example in this issue, our work with Osama Awadelkarim, director of Penn State's Center for Nanotechnology Education and Utilization (CNEU) and their efforts to partner with Pennsylvania colleges, universities, and industries to educate the future semiconductor manufacturing workforce. Be sure to read that article and learn more about this innovative program that is being mimicked by the National Science Foundation.

Everything in this director's message is just scratching the surface, as I could fill an entire magazine with all of our semiconductor capabilities (and a thick one at that!). We strongly encourage you to learn more by visiting mri.psu.edu/chips and/or contacting Daniel Lopez, Liang Professor of Electrical Engineering and Computer Science at CHIPSAct@psu.edu.

So where do we go from here? All of us at Penn State strongly believe that a coordinated national effort with educational, scientific, government, and industrial groups is a must to restore America's top global standing in semiconductors. We envision regional hubs of partnerships that will work to not just develop the next generation of semiconductors but also enable rapid commercialization of these advancements to enable benefits for society's future and drive the economy forward.

Semiconductors are only going to become more important, and our faculty are honored to help lead America's efforts to once again be a global leader. All of our chips are indeed on the table.

Sincerely,

C A Randall

Director, Materials Research Institute

CENTRALIZED FACILITIES POWER EARLY CAREER RESEARCHER'S BIOMATERIAL WORK

THE FACULTY EARLY Career Development (CAREER) Program is the National Science Foundation's (NSF) most prestigious award for early-career faculty, providing valuable financial support for a specific research project and recognizing that faculty's potential as a leader in scientific research and a role model in education.

Fariborz Tavangarian, associate professor of mechanical engineering at Penn State Harrisburg, is one such example, having landed a CAREER award this year for "Achieving Resilience in Brittle Materials Through Bio-inspired Nested Cylindrical Structures."

> "My background was in materials science and engineering, but when I joined the mechanical engineering department at LSU for my Ph.D, I had to take several mechanical engineering courses." Tavangarian said. "My research is interdisciplinary, and my major focus is on biomaterials and nanotechnology. Since I started my faculty career at Penn State Harrisburg, I started researching mechanics and nature-inspired structures."

The nature-inspired structure that Tavangarian focuses on is found on the bottom of the ocean: most sea sponges have a unique microstructure that features sharp-edged structural components known as spicules. These components are composed of a brittle ceramic, silica, that are also tough and flexible.

"These types of sponges are composed of some strands, and when you look at these strands under a microscope, you see they are nested cylindrical structures," Tavangarian said. "Layer upon layer, it's kind of one cylinder inside another cylinder and they are connected through a type of organic material."

This structure is close to what is found in human bones, so Tavangarian's research findings that are being funded by the CAREER award will explore the potential of such a biological-inspired structure for human bone tissue engineering, among other applications. An early boost for his research came in the form of support from the Commonwealth Campuses Research Collaboration Development Program (CCRCDP).

"The CCRCDP grant was one of the grants that helped me build the foundation of the CAREER award proposal," Tavangarian said. "It allowed me to run some tests at the Materials Characterization Lab (MCL), gathering some preliminary data and subsequently enabled me to provide a proof of concept to the NSF reviewers for the CAREER award."

To see the structure, Tavangarian and MCL staff used scanning electron microscopy (SEM). They also used transmission electron microscopy (TEM) which is a technique where beams of electrons are transmitted through a specimen. This process forms an image that is of extremely high resolution, which is important for Tavangarian's research.

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"I trained Fariborz on how to use the TEMs and also operated the TEM for him to get some more recent data for his NSF proposal," said Jennifer Gray, staff scientist, TEM sample prep with MCL. "In addition, I wrote a paragraph for him in that proposal on how the special equipment we have in our TEM facility could be used for beam-sensitive samples to reduce the damage."

Armed with funding from the CAREER award, Tavangarian's research will move forward. He expects to continue working with the centralized resources at Materials Research Institute and the MCL that will enhance his skills and expertise with the right tools necessary for breakthroughs. ■

MATERIALS RESEARCHERS HONORED FOR ACHIEVEMENTS AS ACADEMIC INVENTORS

PENN STATE PROFESSORS Clive Randall and T.C. Mike Chung have been named 2021 fellows of the National Academy of Inventors (NAI).

The distinction honors academic inventors "who have demonstrated a prolific spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development, and the welfare of society," according to NAI.

> "I deeply appreciate the recognition of NAI for this honor," said Chung, professor emeritus of materials science and engineering. "This belongs to my research group members for more than three decades of hard work and for believing in and developing functional polyolefins for various applications, especially relating to the energy storage and green environmental areas."

Chung and Randall join a cohort of 164 prolific academic innovators from around the world in the 2021 class, which will be inducted in June at the NAI annual meeting in Phoenix, Arizona. Collectively, the group holds more than 4,800 U.S. patents.

At Penn State, Chung worked to develop polymer chemistry in the search for new materials with unique chemical and physical properties for physical applications. Chung recently retired after more than 30 years at the University, where he authored more than 230 papers and received 58 U.S. and international patents.

Chung joined Penn State as an associate professor in 1989. He previously served on the senior research staff at Exxon. He received his bachelor of science degree in chemistry from Chung Yuan University and his doctorate in chemistry from the University of Pennsylvania.

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> “It was wonderful news to hear NAI recognized our efforts to combine innovation, science, and engineering of functional oxide materials,” said Randall, distinguished professor of materials science and engineering and director of the Materials Research Institute at Penn State.

Randall is a world leader in ceramics and functional materials. Among his many contributions are the development of novel processing methods such as the fast-sintering processes for multilayer ceramic capacitor devices, a method that has been adopted by major manufacturers, as it permits superior microstructural and dielectric performance. Via fast sintering, trillions of capacitors are manufactured every year, and these capacitors are in all electrical systems. More recently his group discovered and developed cold sintering, a revolutionary process that enables sintering of ceramics at a much lower temperature than traditional sintering. Cold sintering uses much less energy and enables development of new materials.

Randall joined Penn State in 1987 as a research associate in ferroelectrics. He received his bachelor of science degree in physics from the University of East Anglia and his doctoral degree in experimental physics from the University of Essex. He has authored and co-authored more than 500 technical papers and 20 patents. ■

COMMUNITIES, RESEARCHERS JOIN FORCES TO DESIGN FRAMEWORK FOR SUSTAINABLE HOUSING

AS THE EXECUTIVE director of the Global Building Network and associate professor of engineering design and architectural engineering at Penn State, Esther Obonyo applies best research practices to explore what makes environmentally sustainable and climate change resilient structures, from crushing bricks in the lab to visiting Tanzania for field research. Now, she is employing another technique that she says is critical and often lacking or secondary: listening.

With a two-year, $400,000 National Science Foundation Boosting Research Ideas for Transformative and Equitable Advances in Engineering (BRITE) Synergy award, Obonyo is bringing the community voice to the forefront of design criteria by leading the project, “Developing and Validating a Framework for Measuring Resilience in Low-Income Housing in the Post-Pandemic World.”

Obonyo’s research focuses on using sustainable materials to create buildings that can withstand natural disasters as well as crises brought on or exacerbated by climate change, such as extreme heat waves, while also reducing the carbon footprint of the building by requiring less energy to heat or cool it. She said that while researchers have developed many sustainable, resilient solutions, the adoption of these solutions has been slow. To answer why people are not adopting the technology and methods at scale, Obonyo said she wants to focus on the human perspective, with a particular emphasis on vulnerable populations.

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> “We are questioning the targets, metrics, and tools that are used to measure resilience, because a lot of our metrics, tools, and frameworks focus on the physical dimensions,” she said. “Our ultimate goal is still to get the physical assets to perform better, but we need to go beyond that and start looking at the lived experiences of the people within marginalized communities.”

Obonyo said the research is more than academic.

“As I was reflecting on the opportunities for engaging with community members in Philadelphia and Pittsburgh and other places, I realized that a lot of these housing units that are impacted by issues like extreme heat or air quality happen to be women-led, especially by women of color,” she said, noting these key stakeholders are frequently left out of such conversations. “They face significant obstacles, such as a lack of childcare or the potential of lost wages, to engaging in these research conversations.”

To help mitigate these barriers, which are not limited to but overwhelmingly impact women of color over other demographics, Obonyo requested some compensation for participants in the grant proposal. The request was approved. ■

> “I’ve spent my entire career trying obscure the fact that I’m a Black woman in STEM,” Obonyo said. “For the first time, I was bold enough to embrace my identity and feel comfortable enough in my skin to ask, ‘What would limit me as a Black woman from participating in research that could help my community that is being adversely impacted by extreme weather events and experiencing energy burden?’ I’m very excited that we have some resources to help us hear from the people in these communities and, together, we can develop a more equitable, human-centered framework for building designs.”

Credit: Adobe Stock

MAURICIO TERRONES HONORED AS EVAN PUGH PROFESSOR AT PENN STATE

Credit: Nate Follmer

MAURICIO TERRONES, VERNE M. WILLAMAN Professor of Physics and professor of chemistry and of materials science and engineering, has been named an Evan Pugh University Professor, the highest honor that Penn State bestows on a faculty member.

The professorships are named for Penn State's founding president, Evan Pugh, a renowned chemist and scholar who was at the helm of the University from 1859 to 1864. The Evan Pugh Professorships are awarded to faculty members who are nationally or internationally recognized leaders in their fields of research or creative activity; demonstrate significant leadership in raising the standards of the University with respect to teaching, research or creativity, and service; display excellent teaching skills with undergraduate and graduate students who go on to achieve distinction in their fields, and receive support from colleagues who also are leaders in their disciplines.

Through his research, Terrones has made considerable experimental and theoretical contributions to the field of nanoscience — the physico-chemical and biological manipulation of incredibly small structures less than 100 nanometers, or less than a thousand times smaller than the width of a human hair. He studies and builds nanomaterials that exhibit novel phenomena and could potentially have industrial, biomedical and electronic applications, including carbon-based and low-dimensional materials like carbon nanotubes, graphene, and monolayers of transition metal dichalcogenides.

Prior to joining the Penn State faculty in 2011, Terrones was a professor at the Universidad Carlos III in Spain in 2010 and at the Instituto Potosino de Investigación Científica y Tecnológica (IPICYT) in San Luis Potosí, Mexico from 2001 to 2009. He was an Alexander von Humboldt Fellow at the Max-Planck-Institut für Metallforschung in Germany in 1999, and a postdoctoral research fellow at the University of Sussex from 1997 to 1999. Terrones obtained a doctoral degree in chemical physics at the University of Sussex under the supervision of Nobel Laureate Harold W. Kroto in 1997 and a bachelor's degree in engineering physics with first-class honors at Universidad Iberoamericana in Mexico in 1992. ■

Researchers to develop scaffolding for nerve regeneration with $2.14M NIH grant

Penn State researchers are developing citrate-based biodegradable nerve scaffolds, which are shown here.
Credit: Kelby Hochreither/Penn State. All Rights Reserved.

PERIPHERAL NERVES ARE responsible for moving muscles, sensing temperatures, and even inhaling and exhaling; yet they comprise fragile fibers vulnerable to disease and injury. To maximize healing for the easily damaged nerves, Penn State researchers are using a five-year, $2.14 million grant from the National Institutes of Health's National Institute of Neurological Disorders and Stroke to develop a biodegradable nerve scaffold that aims to employ folate and citrate in novel ways.

> "Folate and citrate strengthen different pathways to help tissue regeneration, and we have both in one biomaterial," said principal investigator Jian Yang, professor of biomedical engineering in the Penn State College of Engineering and the Dorothy Foehr Huck and J. Lloyd Huck Chair in Regenerative Engineering in the Huck Institutes of the Life Sciences.

The use of citrate in biomaterials is not new, according to Yang, but the addition of folic acid, or vitamin B9, into the polymer backbone of their nerve scaffold is. Folate — one of the key vitamins found in prenatal vitamins because it plays a critical role in the development of the central nervous system — also plays an important, if lesser known, role in helping the peripheral nervous system develop.

Peripheral nerves have two major components: axons and Schwann cells. Axons transmit signals from the body to the brain and back again. Schwann cells "pave the road" for axons, according to Yang, and folate helps Schwann cells move to the right spot.

"Schwann cells are like the pavement on top of which the axons can grow," said Yang, who also is affiliated with the Penn State Materials Research Institute. "We found that folate can promote Schwann cell migration, or 'paving the road,' which is a critical step to promote nerve regeneration, because the nerves have to cross the gap to grow and reconnect."

This gap, or the nerve defect or spot of damage, is where the researchers will place the engineered and folate-fortified nerve conduit to encourage nerve regeneration. The researchers also can use folate to modify the physical structure of DNA to better control how the cells develop during regeneration.

In addition to developing the nerve conduit scaffold with folate and citrate, the researchers plan to employ photoacoustic imaging to closely monitor how the materials degrade and how the tissue regenerates, along with other outcomes. Co-PI Raj Kothapalli, Penn State assistant professor of biomedical engineering, will lead this noninvasive imaging technique effort.

The other co-investigators on the project, all from Penn State, are: Sulin Zhang, professor of engineering science and mechanics and of biomedical engineering, who also is affiliated with the Materials Research Institute and the Department of Materials Science and Engineering in the College of Earth and Mineral Sciences; Cheng Dong, distinguished professor of biomedical engineering; and Elias Rizk, associate professor of neurosurgery at Penn State College of Medicine and neurosurgeon at Penn State Health. ■

Credit: Pixabay

Grant from Manufacturing PA Initiative to improve glass recycling technology

MORE THAN 12 million tons of glass are produced annually in the United States, but only 25% of glass is recycled and non-soda lime silicate glass compositions used in smartphones and other electronic devices cannot be recycled at all. Penn State recently received funding for the project, "Enabling Improved Glass Recycling Technology and Modeling Tools," to help promote higher recycling rates in Pennsylvania.

On April 8, Gov. Tom Wolf announced a $2.3 million investment in 36 student research projects aimed at advancing innovation in several sectors of manufacturing. The 36 projects are part of Manufacturing PA Initiative's fellowship program. The program embeds the commonwealth's best and brightest graduate and undergraduate students with local manufacturers. Once paired, the students embark on research projects to develop new technologies and advance innovation statewide.

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John Mauro, professor of materials science and engineering at Penn State, will serve as the project's principal investigator. Penn State will partner with Remark Glass, a woman-owned startup company focused on innovative and creative glass recycling, to address several technical challenges facing glass recycling.

> "I am excited to partner with Remark Glass to help find solutions to expand glass recycling opportunities and reduce the amount of glass waste going into landfills," said Mauro. "This funding will also provide a unique opportunity for one of our graduate students."

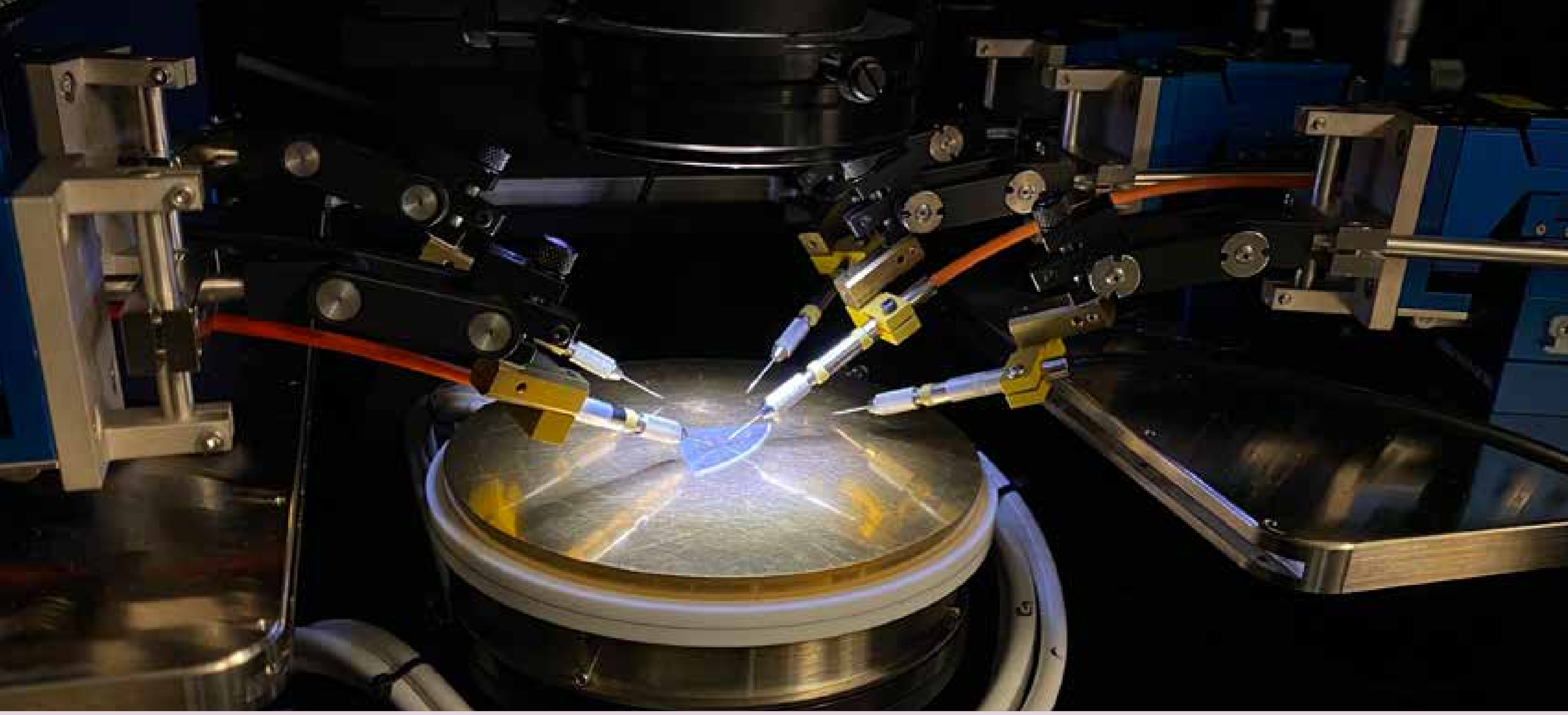
Based in south Philadelphia, Remark Glass was established in 2016 and is Philadelphia's first zero-waste certified company.

"As Philadelphia's first zero-waste certified business, we have earned gold status by diverting at least 90% of the material from our business from becoming landfill waste by creating recycled glass products through various glass making techniques," said Rebecca Davies, co-founder of Remark Glass. "We are looking forward to partnering with Penn State to enhance possibilities for glass recycling."

This project will fund one graduate student to work closely with Mauro and Remark Glass to thoroughly characterize different colors and compositions of glass cullet and develop predictive models to allow for mixing of cullet and use of alternative compositions. Characterization will include viscosity curves for press molding, optical color coordinates to predict and fine-tune glass color, thermal expansion coefficient for thermal shock resistance, and liquidus temperature for quality control. Predictive models will be developed and delivered to Remark Glass to enable the used of mixed-color and mixed-composition cullet and tailor-design glass products and processes for use with recycled glass.

The deliverables from this project will include the first-ever modeling tools specifically to aid in glass recycling, according to Mauro. This will help establish Pennsylvania as a leader in glass recycling technology. ■

Credit: Adobe Stock



Credit: Jennifer M. McCann/Penn State MRI

Penn State to lead $7.5 million study of radiation effects on electronics

ELECTRONICS EMPLOYING WIDE bandgap semiconductors promise better resistance against radiation damage over conventional silicon-based electronics, according to a newly funded national collaboration led by Penn State. To better predict and mitigate radiation-induced damage of wide bandgap semiconductors, the U.S. Department of Defense awarded the team a five-year, $7.5 million Defense Multidisciplinary University Research Initiative Award.

"Most of today's electronics are based on silicon," said Rongming Chu, Thomas and Sheila Roell Early Career Associate Professor of Electrical Engineering, who will spearhead the project. "Wide bandgap semiconductors, such as gallium nitride, have shown advantages over silicon in radio frequency and power electronics. They are also inherently more resistant to radiation due to stronger atomic bonds."

This resistance to radiation, called radiation hardness, protects against damage caused by radiation from high-energy rays and particles. This property, Chu said, makes wide bandgap semiconductors promising candidates for building electronics used in environments with significant radiation, such as outer space. However, researchers have yet to reach the full potential of radiation hardness in wide bandgap semiconductor electronics.

"Preliminary studies have indicated that the radiation resistance appears to be limited by defects in the semiconductors, rather than by the material's intrinsic properties," Chu said. "In this project, we seek to understand the radiation effects of these defects so that we may develop a strategy to redesign the wide bandgap semiconductor device for the ultimate radiation hardness."

Defects in the materials and structures of electronics can range from minor to dire, resulting in device degradation and

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failure. To better understand how radiation causes defect generation and evolution, how these defects affect device operation, and how to redesign future wide bandgap devices for the optimum radiation hardness, Chu said an interdisciplinary team is critical.

Collaborators include Patrick M. Lenahan, distinguished professor of engineering science and mechanics; Miaomiao Jin, assistant professor of nuclear engineering; and Blair R. Tuttle, associate professor of physics, all from Penn State; and Tania Roy, University of Central Florida; B. Reeja Jayan, Carnegie Mellon University, and Michael E. Flatté, University of Iowa. Chu noted that, at Penn State, the team will leverage the tools and experts affiliated with the Radiation Science and Engineering Center and the Nanofabrication Laboratory and Materials Characterization Laboratory at the Materials Research Institute.

“The strength of our project comes from a combination of expertise: my research group’s capabilities on gallium nitride devices, Dr. Lenahan’s expertise in defect spectroscopy, Dr. Jin’s radiation damage modeling, Dr. Tuttle’s defect theory work, Dr. Roy’s electrical characterization of radiation effects, Dr. Jayan’s defect structure characterization and Dr. Flatté’s transport theory work,” Chu said. “The teamwork also extends beyond the investigators of this MURI project — especially Dr. Michael Lanagan, professor of engineering science and mechanics, who was very instrumental in coordinating this multidisciplinary team effort.”

The grant will support 16 graduate students, including 11 at Penn State, to perform multidisciplinary research encompassing physics, computation, materials science, and engineering and electrical engineering as they pursue a variety of master’s degrees and doctorates. ■

Decades in the making: Researchers continue total artificial heart project

DEVELOPMENT OF AN implantable artificial heart that operates wirelessly and reliably for 10 years is the goal of a new Penn State College of Medicine project that received more than $3 million from the National Heart, Lung, and Blood Institute, part of the National Institutes of Health. The device could be a potential solution to the lack of available hearts for people with heart failure who need transplants.

Millions of people in the U.S. suffer from heart failure and while some currently available devices are bridges-to-transplant — including left ventricular assist devices (LVADs) and even one total artificial heart — none are permanent solutions, or destination therapies. Gerson Rosenberg, C. McCollister Evarts, MD, Professor in Artificial Organs, and professor of surgery and biomedical engineering, said that a new generation of options are needed because the demand for donor hearts is greater than the supply.

“An estimated 10,000 people could benefit from a total artificial heart or donor heart each year, and only about 2,000 donor organs become available annually,” Rosenberg said. “Mechanical devices could be beneficial for people who are not candidates for transplant due to their age or other health conditions like high resistance to blood flow in the lungs.”

Gerson Rosenberg holds in his hands the Penn State Heart, a total artificial heart that was first implanted in a patient at Penn State Health Milton S. Hershey Medical Center in 1985. It was used as a bridge to transplant in patients with heart failure and set the stage for continued development of total artificial hearts as a destination therapy. Credit: Penn State College of Medicine

Rosenberg has been working on artificial heart projects since the 1970s. He and his co-principal investigator, Joshua Cysyk, associate professor of surgery, will partner with collaborators from the Division of Applied Biomedical Engineering, whose combined expertise covers areas from electrical and mechanical engineering to surgery, to design the device. They plan to develop a completely implantable total artificial heart that operates wirelessly and reliably for 10 years. It will have both a left and right pump to function as the heart's left and right ventricles.

One advantage to their proposed design is that it will also conform to the anatomy of smaller patients. The pump will have sensors in it to help give it a pulsatile flow, similar to that of a real, 'beating' heart. The sensors will also allow the device to respond to various physiologic conditions like exercise, and will adjust the output of the pumps accordingly.

After building the pump and finessing the automatic control system, the team will test the device to confirm its ability to respond to varying conditions and to make sure the materials are compatible with blood and other biological components of the body so as to avoid clotting or bleeding episodes.

> "This project is a major undertaking and is years in the making, but at Penn State, we have the right experts and facilities to make it possible," Rosenberg said. "If we're successful, this total artificial heart could provide an alternative option to patients in need of a transplant." ■

research SNAPSHOTS

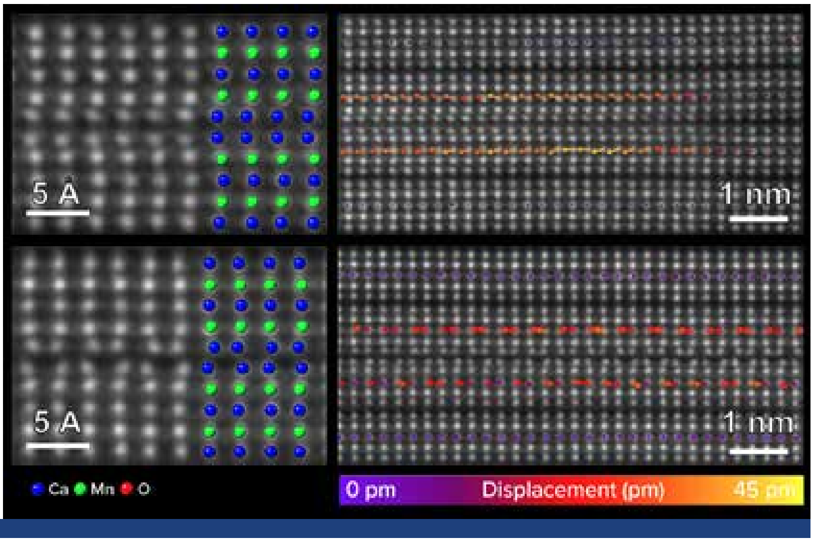
Research Snapshots are brief summaries of significant materials-related breakthroughs by Penn State researchers.

Unique ferroelectric microstructure revealed for first time

By Jamie Oberdick

A TEAM OF RESEARCHERS have observed and reported for the first time the unique microstructure of a novel ferroelectric material, enabling the development of lead-free piezoelectric materials for electronics, sensors, and energy storage that are safer for human use. This work was led by the Alem Group at Penn State and in collaboration with research teams at Rutgers University and the University of California, Merced.

“We would love to design a piezoelectric material that doesn’t have the disadvantages of the current materials,” Nasim Alem, Penn State associate professor of materials science and engineering and the study’s corresponding author, said. “And right now, lead in all these materials is a big disadvantage because the lead is hazardous. We hope that our study can result in a suitable candidate for a better piezoelectric system.”



An atomically resolved scanning transmission electron microscopy (STEM) image of the polar nanoregions (PNRs) embedded in the nonpolar matrix in the layered perovskite material (Ca, Sr)3Mn2O7. Bright contrast in the images can be directly interpreted as the atomic columns in the crystal. Aberration corrected STEM was employed to direct capture the arrangement of the atoms in the (a-type and b-type) polar nanoregions in the crystal and the displacement measurement at picometer precision were performed on the STEM images to extract the distortion in the structure. Credit: Alem Group/Jennifer M. McCann, MRI. All Rights Reserved.

To develop a pathway to such a lead-free material with strong piezoelectric properties, the research team worked with calcium manganate, Ca3Mn2O7 (CMO). CMO is a novel hybrid improper ferroelectric material with some interesting properties.

"The designing principle of this material is combining the motion of the material’s little oxygen octahedra,” said Leixin Miao, doctoral candidate in materials science and first author of the study in Nature Communications. “In the material, there are octahedra of oxygen atoms that can tilt and rotate. The term ‘hybrid improper ferroelectric’ means we combine the rotation and the tilting of the octahedra to produce ferroelectricity. It is considered a ‘hybrid’ because it is the combination of two motions of the octahedra generating that polarization for ferroelectricity. It is considered an ‘improper’ ferroelectric since the polarization is generated as a secondary effect.”

There is also a unique characteristic of CMO’s microstructure that is something of a mystery to researchers.

“At room temperature, there are some polar and nonpolar phases coexisting at room temperature in the crystal,” Miao said. “And those coexisting phases are believed to be correlated with negative thermal expansion behavior. It is well-known that normally, a material expands when heated, but this one shrinks. That is interesting, but we know very little about the structure, like how the polar and nonpolar phases coexist.”

To better understand this, the researchers used atomic-scale transmission electron microscopy.

"Why we used electron microscopy is because with electron microscopy, we can use atomic-scale probes to see the exact atomic arrangement in the structure,” Miao said. “And it was very surprising to observe the double bilayer polar nanoregions in the CMO crystals. To our knowledge, it is the first time that such microstructure was directly imaged in the layered perovskite materials.”

Another benefit of the study was free software developed by the research team, EASY-STEM, that enables easier TEM image data processing. This could potentially shorten the time needed to advance scientific research and move it to practical application.

“The software has a graphical user interface that allows users to input with mouse clicks, so people do not need to be an expert in coding but still can generate amazing analysis,” Miao said. ■

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New granular hydrogel bioink could expand possibilities for tissue bioprinting

By Sarah Small

EVERY DAY IN the United States, 17 people die waiting for an organ transplant, and every nine minutes, another person is added to the transplant waiting list, according to the Health Resources and Services Administration. One potential solution to alleviate the shortage is to develop biomaterials that can be three-dimensionally (3D) printed as complex organ shapes, capable of hosting cells and forming tissues. Attempts so far, though, have fallen short, with the so-called bulk hydrogel bioinks failing to integrate into the body properly and support cells in thick tissue constructs.

Now, Penn State researchers have developed a novel nanoengineered granular hydrogel bioink that makes use of self-assembling nanoparticles and hydrogel microparticles, or microgels, to achieve previously unattained levels of porosity, shape fidelity, and cell integration.

The team published their approach in the journal Small. Their work will be featured on the journal's cover.

"We have developed a novel granular hydrogel bioink for the 3D-extrusion bioprinting of tissue engineering microporous scaffolds," said corresponding author Amir Sheikhi, Penn State assistant professor of chemical engineering who has a courtesy appointment in biomedical engineering. "We have overcome the previous limitations of 3D bioprinting granular hydrogels by reversibly binding the microgels using nanoparticles that self-assemble. This enables the fabrication of granular hydrogel bioink with well-preserved microporosity, enhanced printability and shape fidelity."

To date, the majority of bioinks have been based on bulk hydrogels — polymer networks that can hold a large amount of water while maintaining their structure — with nanoscale pores that limit cell-cell and cell-matrix interactions as well as oxygen and nutrient transfer. They also require degradation and/or remodeling to allow cell infiltration and migration, delaying or inhibiting bioink-tissue integration.

To overcome this issue, scientists in the field began using microgels to assemble tissue-engineering scaffolds. In contrast to the bulk hydrogels, these granular hydrogel scaffolds were able to form 3D constructs in situ, regulate the porosity of the created structures and decouple the stiffness of hydrogels from the porosity.

Cell viability and migration remained an issue, however, Sheikhi said. To attain the positive traits during the 3D printing process, granular hydrogels must be tightly packed together, compromising the space among microgels and negatively impacting the porosity, which in turn negatively impacts cell viability and motility.

Penn State researchers developed a new nanoengineered granular hydrogel bioink, used here to print an image of the Nittany Lion logo. This bioink helps to achieve previously unattained levels of porosity, shape fidelity and cell integration when 3D printing biomaterials. Credit: Provided by Amir Sheikhi. All Rights Reserved.

The Penn State researchers' approach addresses the "jamming" issue while still maintaining the positive traits of the granular hydrogels by increasing the stickiness of microgels to each other. The microgels cling to each other, removing the need for tight packing as a result of interfacial self-assembly of nanoparticles adsorbed to microgels and preserving microscale pores.

The researchers say that this technology may be expanded to other granular platforms made up of synthetic, natural, or hybrid polymeric microgels, which may be assembled to each other using similar nanoparticles or other physical and/or chemical methods, such as charge-induced reversible binding, host-guest interactions, or dynamic covalent bonds.

According to Sheikhi, the researchers plan to explore how the nanoengineered granular bioink could be further applied for tissue engineering and regeneration, organ/tissue/disease models-on-a-chip, and in situ 3D bioprinting of organs. ■

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research SNAPSHOTS

Compost to computer: Bio-based materials used to salvage rare earth elements

By Mariah Chuprinski

WHAT DO CORNCOBS and tomato peels have to do with electronics? They both can be used to salvage valuable rare earth elements, like neodymium, from electronic waste. Penn State researchers used micro- and nanoparticles created from the organic materials to capture rare earth elements from aqueous solutions.

Their findings, available online now, will also be published in the November issue of Chemical Engineering Journal.

“Waste products like corncobs, wood pulp, cotton, and tomato peels often end up in landfills or in compost,” said corresponding author Amir Sheikhi, assistant professor of chemical engineering. “We wanted to transform these waste products into micro- or nanoscale particles capable of extracting rare earth elements from electronic waste.”

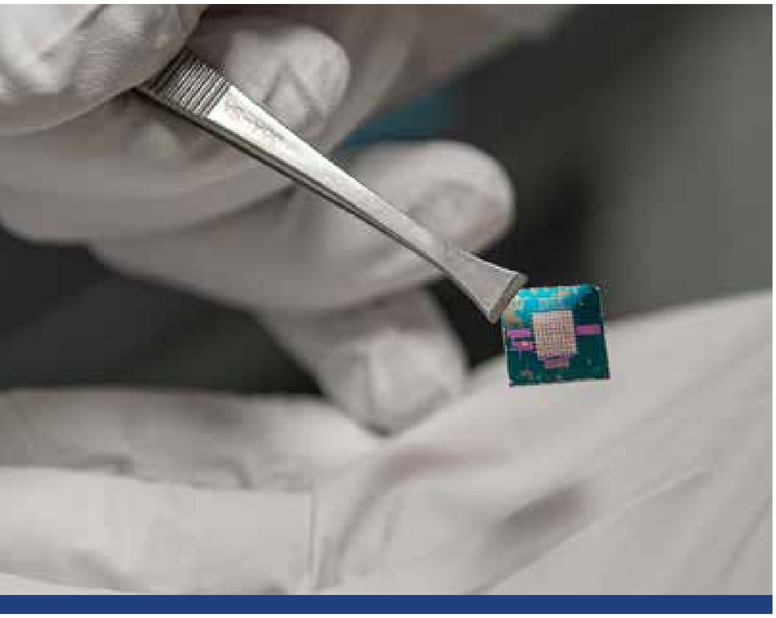
Rare earth metals are used to manufacture strong magnets used in motors for electric and hybrid cars, loudspeakers, headphones, computers, wind turbines, TV screens, and more. However, mining these metals proves challenging and environmentally costly, according to Sheikhi, as large land areas are required to mine even small amounts of the metals. Instead, efforts have turned to recycling the metals from electronic waste items like old computers or circuit boards.

The challenge lies in efficiently separating the metals from refuse, Sheikhi said.

“Using the organic materials as a platform, we created highly functional micro- and nanoparticles that can attach to metals like neodymium and separate them from the fluid that surrounds them,” Sheikhi said. “Via electrostatic interactions, the negatively-charged micro- and nano-scale materials bind to positively-charged neodymium ions, separating them.”

To prepare the experiment, Sheikhi’s team ground up tomato peels and corncobs and cut wood pulp and cotton paper into small, thin pieces and soaked them in water. Then, they chemically reacted

Smart chip senses, stores, computes, and secures data in one low-power platform



By Mariah Chuprinski

DIGITAL INFORMATION IS everywhere in the era of smart technology, where data is continuously generated by and communicated among cell phones, smart watches, cameras, smart speakers, and other devices. Securing digital data on handheld devices requires massive amounts of energy, according to an interdisciplinary group of Penn State researchers, who warn that securing these devices from bad actors is becoming a greater concern than ever before.

Led by Saptarshi Das, Penn State associate professor of engineering science and mechanics, researchers developed a smart hardware platform, or chip, to mitigate energy consumption while adding a layer of security. The researchers published their results on June 23 in Nature Communications.

Penn State materials science and engineering researchers used molybdenum disulfide, a 2D material, to create a low-power cryptographic chip less than one nanometer thick. Credit: Kelby Hochreither/Penn State. All Rights Reserved.

these materials in a controlled fashion to disintegrate them into three distinct fractions of functional materials: microproducts, nanoparticles, and solubilized biopolymers. Adding the microproducts or nanoparticles to neodymium solutions triggered the separation process, resulting in the capture of neodymium samples.

In this most recent paper, Sheikhi improved upon the separation process demonstrated in previous work and extracted larger sample sizes of neodymium from less concentrated solutions.

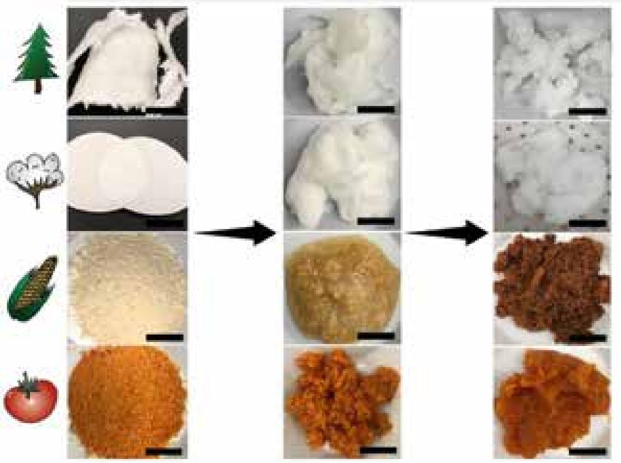
Sheikhi plans to extend his separation mechanism into real-world scenarios and partner with interested industries to further test the process.

“In the near future, we want to test our process on realistic industrial samples,” Sheikhi said.

“We also hope to tune the selectivity of the materials toward other rare earth elements and precious metals, like gold and silver, to be able to separate those from waste products as well.”

In addition to Sheikhi, Mica Pitcher, Penn State doctoral student in chemistry and first author on the paper; Breanna Huntington, Penn State undergraduate student in agricultural and biological engineering; and Juliana Dominick, Penn State undergraduate student in biomedical engineering, contributed to the paper.

Penn State supported this work. ■



After soaking the materials in water (as shown in middle column), Penn State researchers chemically reacted shredded wood pulp, cotton paper, and ground corncob and tomato peels to convert them into microproducts, nanoparticles, and solubilized biopolymers (third column). Adding these microproducts or nanoparticles to solutions containing the rare earth element neodymium triggered the separation process, allowing for capture of the neodymium. Credit: Sheikhi Research Group. All Rights Reserved.

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“Information from our devices is currently stored in one location, the cloud, which is shared and stored in large servers,” said Das, who also is affiliated with the Penn State School of Electrical Engineering and Computer Science, the Materials Research Institute, and the College of Earth and Mineral Sciences’ Department of Materials Science and Engineering. “The security strategies employed to store this information are extremely energy inefficient and are vulnerable to data breaches and hacking.”

Cloud encryption is a current mode of security that converts data into a code to prevent unauthorized access. Popular messaging system WhatsApp, for example, uses the method, theoretically ensuring only the devices involved in the chat can access private messages. However, in practice, cloud encryptions are vulnerable to data leaks and are frequent targets for adversaries, according to researchers.

Commonly used to make transistors used in cellphones, silicon would not work to build a transistor small enough to save on energy use, researchers said. Instead, they turned to 2D materials, specifically molybdenum disulfide (MoS_2), which is less than one nanometer thick, to create a low-power cryptographic chip. Penn State collaborators Joan Redwing, distinguished professor of materials science and engineering and electrical engineering, and Nicholas Trainor, a doctoral student in materials science and engineering, worked together to synthesize the MoS_2 needed to create the chip.

The chip employs 320 MoS_2 transistors that each have a sensing unit, a storage unit and a computing unit to encrypt the data. To test the strength of the encryption process, researchers used machine learning algorithms, which allowed them to study the output patterns and predict input information.

“We found that the advanced machine learning techniques couldn’t decode the encrypted information, reinforcing the resilience of the encryption process against machine learning attacks,” Das said. “Without prior knowledge of the information channels and decoding variables, it is extremely difficult to decode the information.”

Additionally, the researchers said, the energy consumed in encrypting the information was significantly less than silicon-based security methods. The result was a low-power, all-in-one chip that could sense, store, compute, and communicate information among connected devices — a potential solution for users who want added security but cannot afford to drain their handheld device batteries in day-to-day use. ■

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New type of semiconductor may advance low-energy electronics

By Jamie Oberdick

A RESEARCH PARTNERSHIP BETWEEN Penn State and the Massachusetts Institute of Technology (MIT) could enable an improved method to make a new type of semiconductor that is a few atoms thin and interacts with light in an unusual way. This new semiconductor could lead to new computing and communications technologies that use lower amounts of energy than current electronics.

The new type of semiconductor, tin selenide (SnSe), would be useful for developing a new type of electronics known as "photonics" that use particles of light, or photons, to store, manipulate, and transmit information. Traditional electronics use electrons to do this, while photonics use photons. Tin selenide is a binary compound consisting of tin and selenium in a 1:1 ratio.

The material has a peculiar interaction with light that gives it great potential for use in electronics.

“It can be described as a material that has two different colors, meaning that depending on the orientation that you look at it, you will observe a different color,” said Wouter Mortelmans, a postdoctoral associate in the Department of Materials Science and Engineering at MIT, and lead author of the study. “This peculiar optical property could be very useful to compute, store, or transmit information using light.”

To make use of these orientation-dependent properties, it is very important that the fabrication of the material is done with atomic-precision control, said Mortelmans. The dependence of color on material orientation would enable faster and easier inspection of material quality.

“We need a reliable way to make the material, to manufacture devices to spec, without worrying about random, natural variations,” said Rafael Jaramillo, Thomas Lord Associate Professor of Materials Science and Engineering at MIT and senior author of the study published in ACS Nano.

The key to enabling such precision, defect-free material is a process which can be challenging for atomically thin semiconductors known as epitaxy.

“Epitaxy can be imagined as similar to building with Legos, where the material of interest is broken up into small individual unit cells of either triangular or rectangular Lego bricks,” said Maria Hilse, assistant research professor, thin films-MBE, with the Penn State Materials Research Institute’s 2D Crystal Consortium (2DCC). “The base is an ultra-clean host crystal substrate that allows for a certain shape of ‘Lego’ bricks to be put on it. We select this starting substrate plate, ideally, so that it fits perfectly with the crystal structure of the material we want to compose, i.e., our Lego bricks. In the case of SnSe, we would have a pool of rectangular-shaped Lego bricks that we want to assemble on a rectangular-shaped Lego base plate, which is an aluminum oxide (11-20) surface.”

The study was enabled in part by a research relationship between Jaramillo and the 2DCC. The 2DCC is a national user facility supported by the National Science Foundation that is focused on advancing the synthesis of 2D layered chalcogenides for next-generation electronics and quantum technologies.

“Roughly half of the experimental work was performed at the 2DCC, with hands-on collaboration between Drs. Mortelmans and Hilse,” Jaramillo said. “Working with the 2DCC greatly expanded the set of experimental capabilities that we could work with, making this project much more rigorous and convincing than it otherwise would have been. In particular, early discussions with Dr. Hilse and others there were important for motivating and de-risking the work.” ■

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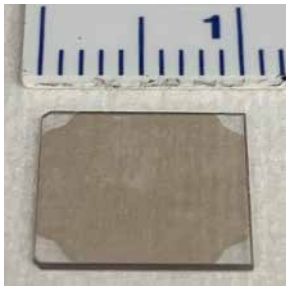
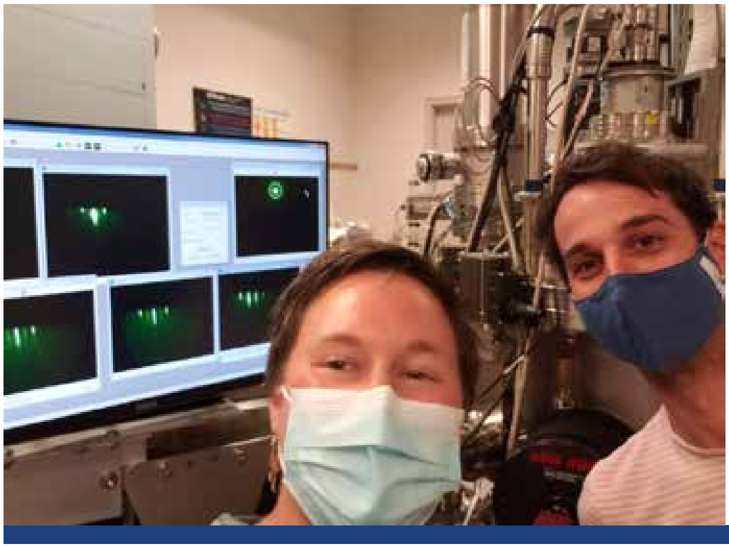
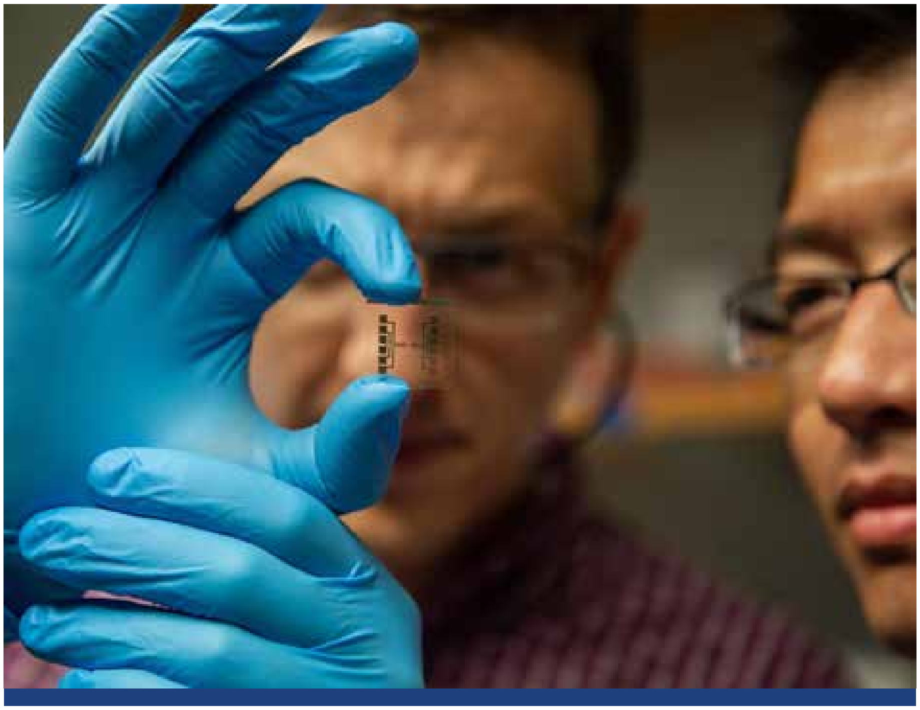


Nine layers of SnSe that were epitaxially grown on an a-plane sapphire substrate. Credit: Wouter Mortelmans/MIT. All Rights Reserved.



Maria Hilse, assistant research professor, thin films-MBE with the 2DCC, left, and Wouter Mortelmans, postdoctoral associate in the Department of Materials Science and Engineering at MIT, right, conduct epitaxial growth runs in the stainless steel reactor in the background during Mortelmans' visit to the 2DCC in October 2021. Credit: Maria Hilse/MRI.



Penn State researchers used a new laser writing technique to develop the first highly customizable microscale gas sensing devices. Credit: Kelby Hochreither/Penn StateAll Rights Reserved.

Laser writing may enable 'electronic nose' for multi-gas sensor

By Ashley J. WennersHerron

ENVIRONMENTAL SENSORS ARE a step closer to simultaneously sniffing out multiple gases that could indicate disease or pollution, thanks to a Penn State collaboration. Huanyu "Larry" Cheng, assistant professor of engineering science and mechanics in the College of Engineering, and Lauren Zarzar, assistant professor of chemistry in Eberly College of Science, and their teams combined laser writing and responsive sensor technologies to fabricate the first highly customizable microscale gas sensing devices.

They published their technique this month in Applied Materials & Interfaces, a journal of the American Chemical Society.

According to Cheng, the challenge is creating devices with the desired properties that still can be tailored with the infrastructure needed for precise and accurate sensing of different target gases at the same time. That's where Zarzar's expertise with laser writing comes in.

Her research group developed the laser-induced thermal voxel process, which enables the simultaneous creation and integration of metal oxides directly into sensor platforms. Metal oxides are materials that react to various compounds, triggering the sensing mechanism. With laser writing, the researchers dissolve metal salts in water, then focus the laser into the solution. The high temperature decomposes the solution, leaving behind metal oxide nanoparticles that can be sintered onto the sensor platform.

The process streamlines previous methods, which required a pre-defined mask of the planned pattern. Any changes or adjustments required the creation of a new mask — costing time and money. Laser writing is "maskless," according to Zarzar, and, when combined with the thermal voxel process, it allows for the rapid iteration and testing of multiple designs or materials to find the most effective combinations.

"Precise patterning is also a necessary component for the creation of 'electronic noses,' or arrays of sensors that act like a nose and can precisely detect multiple gases at the same time," said Alexander Castonguay, graduate student in chemistry and co-first author on the paper. "Such precise detection requires the patterning of different materials in close proximity, at the thinnest microscale. Few patterning techniques have the resolution to do this, but the approach detailed in this study does. We plan to use the techniques and materials described here to develop electronic nose prototypes."

The researchers tested five different metals and metal combinations currently used in sensors. According to Castonguay, the point where different metal oxides touch, called a heterojunction, cultivates a unique environment at the interface of the two materials that enhances the response of gas sensors. The team found that a heterojunction of copper oxide and zinc oxide has a five to 20-fold enhanced response to the tested gases — ethanol, acetone, nitrogen dioxide, ammonia, and hydrogen sulfide — over just copper oxide.

"This finding supports other reports in the scientific literature that the creation of mixed oxide systems can lead to significant increases in sensor response and demonstrates the efficacy of the laser-induced thermal voxel technique for mixed-oxide gas sensor fabrication," Castonguay said. "We hope by pooling the laser writing knowledge of the Zarzar group with the wearable sensor expertise of the Cheng group, we will be able to expand our capabilities to create novel, customizable sensors." ■

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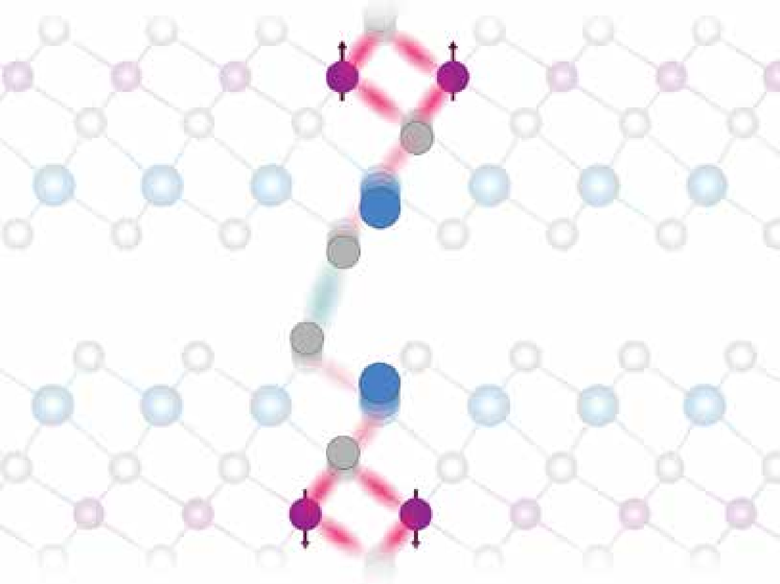

This illustration depicts atomic vibrations, or phonons, in the crystalline lattice structure of manganese bismuth telluride. The discovery that these vibrations can tune weak magnetic bonds between the layers of this 2D material could unlock special properties and pave the way for its use in next generation electronic devices Credit: Penn State. All Rights Reserved.

Scientists find 'knob' to control magnetic behavior in quantum material

By Matthew Carroll

MAGNETISM, ONE OF the oldest technologies known to humans, is at the forefront of new-age materials that could enable next-generation lossless electronics and quantum computers. Researchers led by Penn State and the university of California, San Diego have discovered a new 'knob' to control the magnetic behavior of one promising quantum material, and the findings could pave the way toward novel, efficient, and ultra-fast devices.

"The unique quantum mechanical make-up of this material — manganese bismuth telluride — allows it to carry lossless electrical currents, something of tremendous technological interest," said Hari Padmanabhan, who led the research as a graduate student at Penn State. "What makes this material especially intriguing is that this behavior is deeply connected to its magnetic properties. So, a knob to control magnetism in this material could also efficiently control these lossless currents."

Manganese bismuth telluride, a 2D material made of atomically thin stacked layers, is an example of a topological insulator, exotic materials that simultaneously can be insulators and conductors of electricity, the scientists said. Importantly, because this material is also magnetic, the currents conducted around its edges could be lossless, meaning they do not lose energy in the form of heat. Finding a way to tune the weak magnetic bonds between the layers of the material could unlock these functions.

Tiny vibrations of atoms, or phonons, in the material may be one way to achieve this, the scientists reported April 8 in the journal Nature Communications.

The scientists at Penn State studied the material using a technique called magneto-optical spectroscopy - shooting a laser onto a sample of the material and measuring the color and intensity of the reflected light, which carries information on the atomic vibrations. The team observed how the vibrations changed as they altered the temperature and magnetic field.

As they altered the magnetic field, the scientists observed changes in the intensity of the phonons. This effect is due to the phonons influencing the weak inter-layer magnetic bonding, the scientists said.

Scientists at UC San Diego conducted experiments to track these atomic vibrations in real time. The phonons oscillate faster than a trillion times a second, many times faster than modern computer chips, the scientists said. A 3.5 gigahertz computer processor, for example, operates at a frequency of 3.5 billion times per second.

Further research is needed to directly use the magnetic knob, the scientists said. But if that can be achieved, it could lead to ultra-fast devices that can efficiently and reversibly control lossless currents.

"A major challenge in making faster, more powerful electronic processors is that they heat up," said Venkatraman Gopalan, professor of materials science and engineering and physics at Penn State, Padmanabhan's former adviser, and co-author of the paper. "Heating wastes energy. If we could find efficient ways to control materials that host lossless currents, that would potentially allow us to deploy them in future energy-efficient electronic devices." ■

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Setting a Course for America's Semiconductor Future

Credit: Adobe Stock

And Penn State's Role

SEMICONDUCTORS ARE A big reason as to why you are reading this. This is not a reference to your interest in semiconductors as a subject, but the actual production of this magazine. Even if you are reading the print version of this article and not the online version, semiconductors played a role in creating that hard copy via word processing, graphic design, digital photography, and even the printer that printed the pages. Such is the ubiquitousness of semiconductor chips in our current society.

This level of "everywhere" with semiconductor chips will only increase as technology moves forward. This will lead to some real challenges for our future, from reversing the drop in American share of global semiconductor production to the hunt for a replacement material for silicon. In response to this, a bill was signed this August that sent a charge through the American semiconductor world, from industry to academia.

The bipartisan CHIPS (Creating Helpful Incentives to Produce Semiconductors) and Science Act of 2022 was signed into law on Aug. 9 by President Joe Biden, with a goal of providing federal aid to encourage the construction of semiconductor manufacturing facilities in the United States and to boost scientific research and development. This is a worthy endeavor, for the reasons mentioned above, but it is also a huge endeavor. Passing a law this expansive means the work does not stop when it passes, but it just begins.

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While the CHIPS and Science Act is not just limited to semiconductors (it also includes many investments in basic science research), it also includes $52 billion in investment in American semiconductor manufacturing capabilities.

“The future of semiconductor devices will be based on a broad spectrum, a diverse portfolio of materials and structure, smart manufacturing, sophisticated packaging solutions, innovative R&D, and perhaps most importantly, the development of an American workforce that has the capabilities to pull all of this off,” said Clive Randall, director of the Materials Research Institute (MRI).

Penn State and the Material Research Institute are well-positioned to lend a helping hand making this vision come to fruition. The University receives a perennial high ranking for materials research in the National Science Foundation’s (NSF) Higher Education Research and Development (HERD) survey, most recently number one in the nation for materials science and number two in the nation for materials engineering. These achievements are enabled by the tools and technical staff expertise in MRI facilities, such as the Nanofabrication Laboratory, the NSF national user facility the 2D Crystal Consortium, the Materials Characterization Laboratory, and the Institute for Computational and Data Science.

“Materials science and engineering shape the world around us, making the marvels of the information age possible, providing us with clean and affordable energy, transporting us on land, sea, and air, and keeping us connected with friends and colleagues thousands of miles away,” Daniel Lopez, Penn State Liang Professor of Electrical Engineering and Computer Science and MRI Nanofabrication Laboratory technical director. “Such unprecedented achievements of technology and engineering have their foundation in the discovery science that results in materials, devices, and opportunities to enhance the quality of people's lives."

As Randall noted, this is a full spectrum effort, and beyond research wins, Penn State is also a recognized leader in the education and development of the semiconductor workforce. Examples of this include the Center for Nanotechnology Education and Utilization, which as prepared approximately 1,000 students to work in the semiconductor industry, and the Center for Nanotechnology Applications and Career Knowledge, an NSF-supported advanced education and workforce development center.

> “Nowadays, universities and colleges in the USA contribute to about 55% of the semiconductor workforce,” Lopez said. “Thanks to the CHIPS and Science Act’s programs, it is expected that the demand for workers trained in the multiple aspects of semiconductors and microelectronics manufacturing will increase more than twice in the next five years. This represents a formidable challenge for American universities because we are not ready to generate such a large number of professionals. We must identify novel paradigms to foster collaborations between universities and industry that attract a larger and more diverse population of students and specialists across the U.S.”

Credit: Corey Beasley

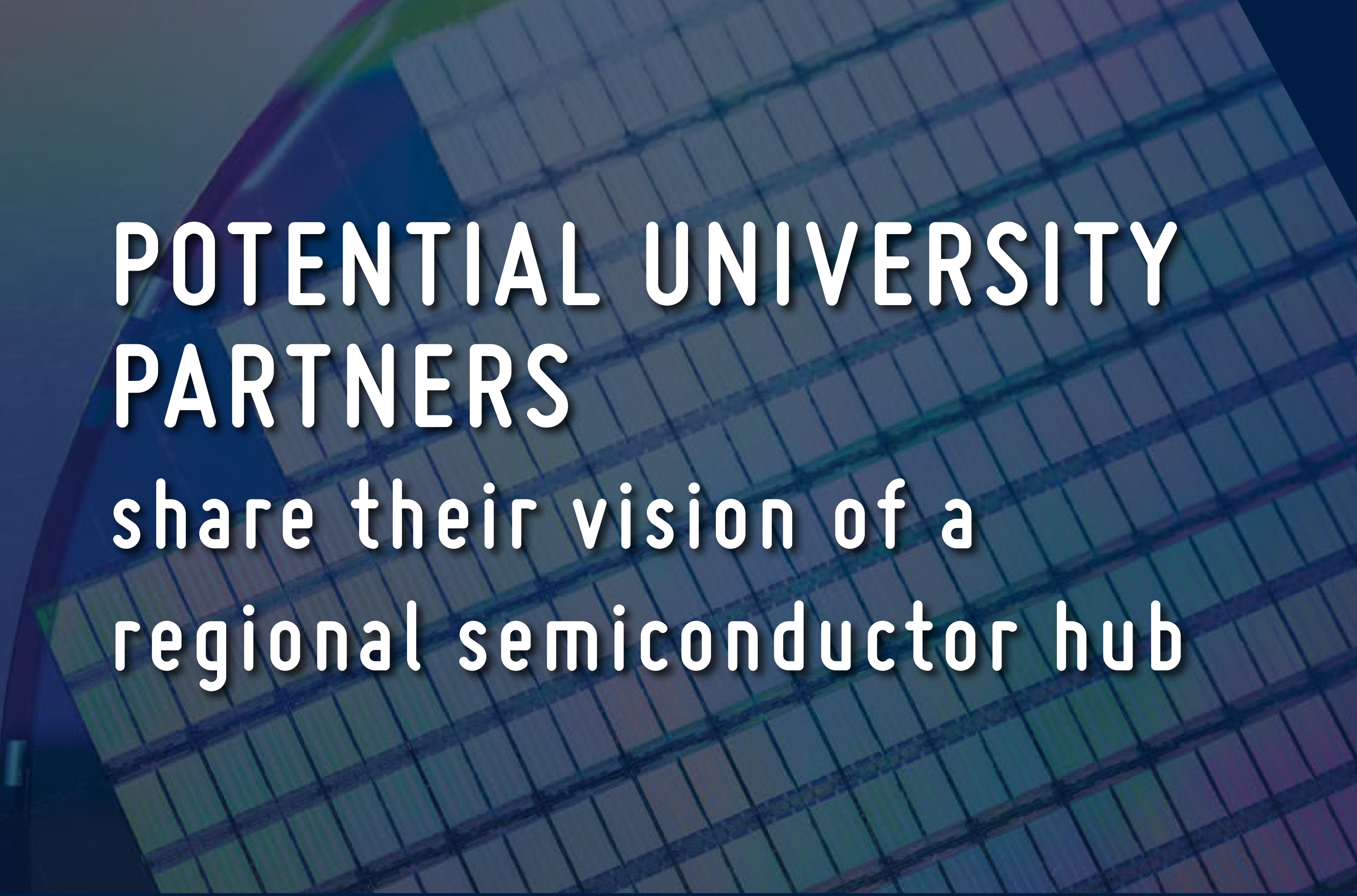
Credit: Corey Beasley

A major focus of the CHIPS and Science Act is it will create regional hubs that will help regions of the country that have limited job opportunities. Currently, part of the planning around semiconductors at Penn State is to build on the partnerships with industry (currently more than 100 companies), government, and other educational institutions (250 independent organizations in the last five years) to create a regional hub with a small group of other universities to develop new materials, a skilled workforce, and new projects.

On Sept. 16, while a guest on the *New York Times* podcast *The Ezra Klein Show*, Felicia Wong, president and CEO of the think tank The Roosevelt Institute, echoes the importance of this concept in helping states with large rural populations like Pennsylvania improve their economy.

"...one of the important pieces of this legislation is that it does create regional hubs. And let's just think about this for a second," Wong said. "One of the major problems with our current economy is inequality, not just between the top 1% and the lowest income earners, but it's also regional inequalities. You see whole parts of this country that really have no jobs to speak of. And there are very few anchor institutions — schools, universities, community colleges, hospitals. You see whole places in this country that don't have private sector investment, and also don't have these kinds of public institutions."

The stakes for everyone in America are obviously quite high. In this special section, we demonstrate how Penn State is helping to push us forward into the new, exciting semiconductor world envisioned by the CHIPS and Science Act. ■



POTENTIAL UNIVERSITY PARTNERS

share their vision of a regional semiconductor hub

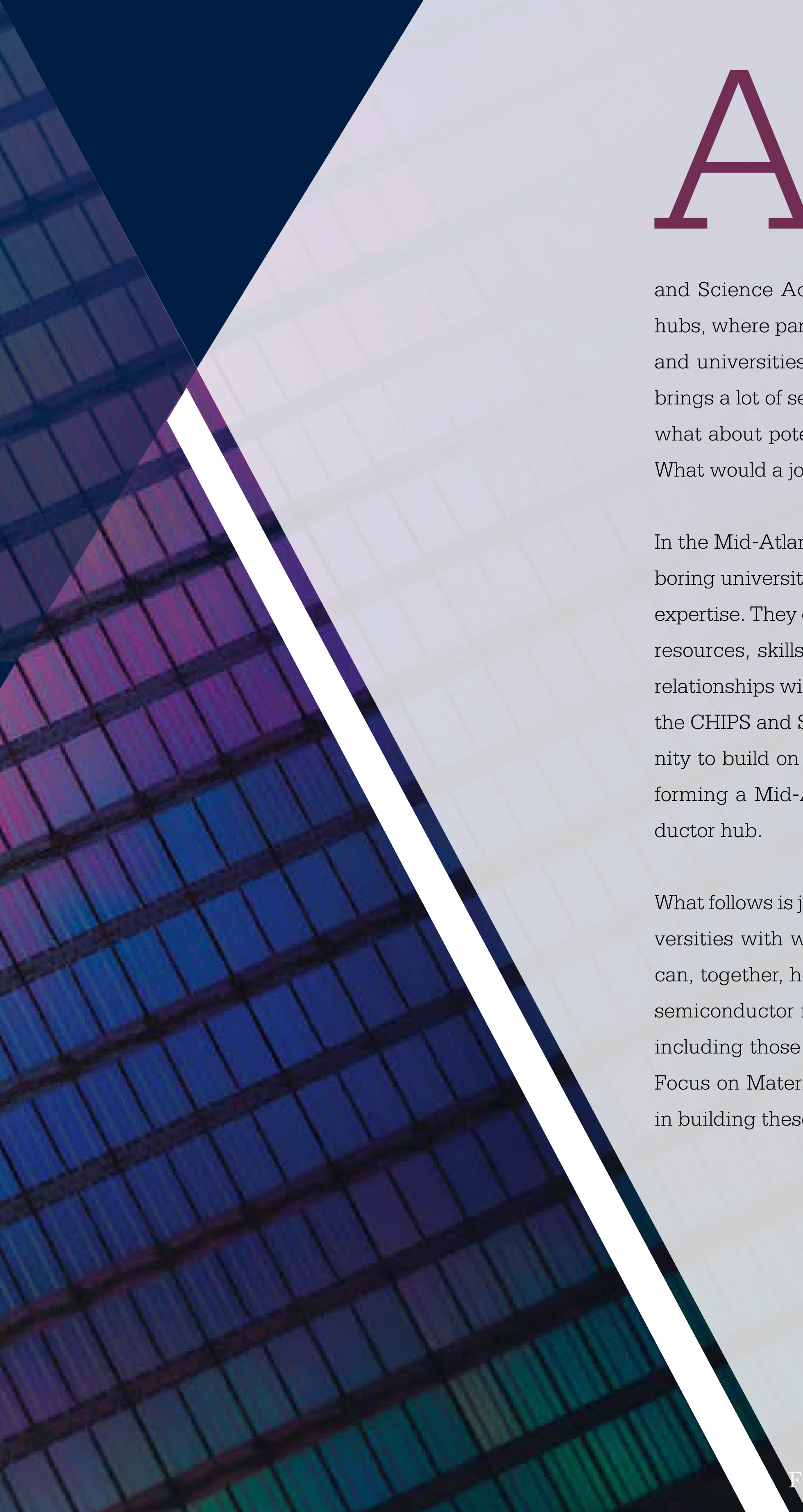
PRINCETON UNIVERSITY

NYU

UNIVERSITY OF MARYLAND

UNIVERSITY OF DELAWARE

Credit: Adobe Stock



AS OUTLINED IN the CHIPS and Science Act, regional hubs would play a key role in an American semiconductor future.

Part of what will help make the CHIPS and Science Act a success is the concept of regional hubs, where partnerships among industry, government, and universities like Penn State will thrive. Penn State brings a lot of semiconductor expertise to the table, but what about potential university partners in the region? What would a joint university partnership look like?

In the Mid-Atlantic region, Penn State has many neighboring universities that also hold a lot of semiconductor expertise. They complement each other and offer unique resources, skills, and strengths. Penn State has forged relationships with these universities over the years, and the CHIPS and Science Act offers a significant opportunity to build on these connections and take the lead in forming a Mid-Atlantic version of a regional semiconductor hub.

What follows is just a small sampling of neighboring universities with whom Penn State is exploring how they can, together, help to chart a new course for America's semiconductor future. We will highlight other partners, including those in industry, over the next few issues of Focus on Materials as we update the exciting progress in building these regional hubs.

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Credit: Adobe Stock

UNIVERSITY PARTNERS

PRINCETON UNIVERSITY

As far as contribution to a regional partnership, Craig Arnold, vice dean for innovation and Susan Dod Brown Professor of Mechanical and Aerospace Engineering at Princeton University, touts Princeton's diversity of semiconductor-related strengths.

"Princeton University has an incredibly diverse and deep community in the area of semiconductors covering different materials, different processing methods, etc.," Arnold said. "In addition, we have a 15,000-square foot cleanroom with a corresponding packaging lab and a soft materials processing lab. Within our facility, we have a number of companies that work with us, and we have close ties to the Princeton Plasma Physics Laboratory, a Department of Energy national lab that focuses on Plasma processing in semiconductor manufacturing."

While Princeton, like Penn State, boasts manifold strengths in semiconductor research, Princeton is anticipating a regional partnership will have many benefits for all partners, and beyond. "Given the scale and diversity of the semiconductor industry, it is critical that universities collaborate," Barry Rand, associate professor of electrical and computer engineering and the Andlinger Center for Energy and the Environment, said. "Without such collaborations, researchers would not be exposed to the breadth, reach, and scope of the semiconductor ecosystem."

Similar thinking, Rand said, goes for partnerships with industry, especially for a key aspect of the CHIPS and Science Act, workforce development.

"Additionally, such partnerships bring considerable value to academic research, as industrial researchers understand the critical problems that require urgent solutions," Rand said. "These problems will thus lead to the greatest impact for society and generate a well-trained workforce. I think an ideal hub would include a combination of industry, government, and academia. Colleges and universities would play the key roles of workforce training and advanced research and development."

NYU

New York University is developing two new research facilities in Brooklyn, New York that are available to any potential partner in a regional semiconductor hub. One is a cutting-edge nanofabrication facility and another is a state-of-the-art THz measurement facility. These will fuel advanced research in quantum and THz electronics in the United States. These new facilities can also serve as training grounds for future semiconductor workers. This would be a perfect complement to the global-leading efforts for workforce development at Penn State, including the extensive work described in this issue of Focus on Materials being done by Osama Awadelkarim as director of the Center for Nanotechnology Education and Utilization.

“These two cutting-edge research facilities at NYU support several Research Centers within NYU in the fields of Quantum and Communications,” Davood Shahrjerdi, associate professor of electrical and computer engineering with NYU and director of the NYU Nanofabrication Facility, said. “A hallmark of these research centers is their strong connections with the semiconductor industry. Lastly, these research centers at NYU have well-established workforce development pipelines for educating the next generation of diverse engineers and researchers in the field of semiconductor manufacturing.”

Shahrjerdi envisions that a regional hub featuring Penn State and other universities would create a synergy of capabilities around semiconductors, while a partnership with industry would help set the agenda.

The inter-university partnership is crucial for amplifying the unique strengths of different universities in accomplishing this mission, facilitating a closer collaboration and development of unified strategies toward the lab-to-fab translation of cutting-edge research on unconventional semiconductors,” Shahrjerdi said. “At the same time, the industrial partnership is crucial for understanding the needs of the semiconductor industry.”

The future semiconductor hub in the mid-Atlantic would come at a crucial time, Shahrjerdi believes, not just because of the need to the United States to revitalize its chip industry, but also at a time when new technology is needed to move the field forward.

“The semiconductor industry is at a critical juncture as the conventional silicon transistor scaling is running out of steam,” he said. “The ideal hub will focus on radical scientific and technological innovations that can result in groundbreaking technologies with an emphasis on their translations into manufacturing settings. It will also have a strong workforce development component for training the next generation of engineers and researchers necessary for this next step.”

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UNIVERSITY OF MARYLAND

The University of Maryland brings a diverse set of research groups and facilities for the design, testing, and analysis of semiconductor devices. This includes their Institute for Systems Research, which works in hardware design and security, bioelectronics, RF electronics, and edge computing hardware, among others, and the Center for Advanced Life Cycle Engineering, which provides expertise in reliability analysis, accelerated testing, risk mitigation, and life cycle analysis for advanced electronics systems.

However, like in real estate, a Maryland strength is location, location, location – In this case, their proximity to our nation's capital, Washington, D.C.

“One of our strengths that we have is our close proximity and strong collaborations with local defense industry and defense labs which allows us to partner on addressing the unique needs found in government electronics,” Samuel Graham, Jr., dean of the A. James Clark School of Engineering at the University of Maryland, said.

Graham said that Maryland is excited to participate in a semiconductor research hub because it would create a “value chain” for the future of chips.

“An ideal hub would include strengths in the critical aspects of design, manufacturing, packaging, and testing to allow for prototyping and creating new microelectronics technologies,” Graham said. “It will also provide a place for workforce development through experiential learning or training on critical pieces of this value chain.”

For Pamela Abshire, professor of electrical and computer engineering at the University of Maryland, a challenge to tackle is the scale of semiconductors. Microelectronics is a big field, responsible for nearly a quarter of global GDP.

"It is hard for any one institution to cover all of that ground, so partnerships among universities and with government and industry take on a critical role as our nation begins to reinvest in domestic capability in semiconductors and microelectronics,” Abshire said. “In many other countries, universities work much more closely with industry than in the U.S. We can't build a strong American semiconductor industry without coordination, collaboration, and frequent interactions and feedback from our industrial partners.”

These points, Abshire noted, were among the main takeaways from the Mid-Atlantic Microelectronics and Heterogeneous Integration Workshop, where colleagues from academia, industry, and government gathered in August at the University of Maryland College Park.

“The main take-home messages included, first, strong support for regional prototyping capabilities, second, advantages of better coordination among academia, government, and industry, and third, the critical need for developing and sustaining the microelectronics workforce,” Abshire said.

Credit: Adobe Stock

UNIVERSITY OF DELAWARE

One of the research strengths of the University of Delaware fits in well with the CHIPS and Science Act – photonic integrated circuits.

“We have a history here at Delaware with optoelectronic devices and integrated photonics on silicon and other platforms,” said Jamie Phillips, professor and chair of the Department of Electrical and Computer Engineering at the University of Delaware. “One of our key faculty members, Dennis Prather, is an expert in thin film lithium niobate. We have one of the only sources of thin film lithium niobate domestically in the US, which is an enabling technology for photonics on a chip. He co-founded a company, Phase Sensitive Innovations, that has commercialized that technology.”

Other strengths at Delaware include a user facility for epitaxial growth, emerging research in the field of quantum science and technology, and on the educational side, a new multidisciplinary quantum science and engineering graduate program that would feed into CHIPs Act-related semiconductor activities.

Phillips sees partnerships among universities as key because of important factors such as redundancy of facilities, where a partner can offer their facility to another partner in the case of something such as a clean room issue or equipment failure. They can also work together to incubate startup companies and offer their facilities to these new-born entities.

“It’s very difficult and prohibitively expensive to establish a cleanroom facility on your own but being able to take advantage of an open nanofab that they can use to develop their products is critical for further innovation and new technologies,” Phillips said.

For a potential Mid-Atlantic university partnership for semiconductor research and development, Phillips sees a synergistic relationship where partners with complementary strengths would be able to create new centers where faculty from various semiconductor subcategories would be able to combine expertise and resources to create something bigger.

“I think there are some really powerful selling points in enabling, say a Mid-Atlantic, New York to Washington, D.C. type of a research hub,” Phillips said. “We would have a geographical advantage given all the universities and other entities around us, particularly in the defense sector."

PARTNERSHIPS TO CREATE A SEMICONDUCTOR REGIONAL POWERHOUSE IN THE MID-ATLANTIC

As mentioned, this is just a sampling of potential partners in a regional semiconductor research and workforce development hub that Penn State is leveraging prior relationships to build, and there will be more partners highlighted in upcoming issues. Given Penn State is a long-time leader in both materials research and workforce development, the University is well-positioned to show the way to building a regional, Mid-Atlantic hub that leverages our strengths and our partners’ strengths. These hubs will have a transformative impact in the advancement of U.S. semiconductor manufacturing, potentially creating a powerhouse partnership among the private sector, academia, and government-funded entities.

American scientists developed these chips as part of the Moon landing program in the 1960s, and we led the industry for decades. This network of facilities, semiconductor materials research leaders, and innovative workforce development and training that Penn State is coordinating will enable America to reassert its leadership role in the world’s semiconductor industry.

Organic semiconductors' glowing potential

MANY PEOPLE THINK of semiconductors as vital for computers, but they have another characteristic that makes them valuable: the ability to efficiently absorb and emit light.

This property of semiconductors enables high-efficiency LED lighting, which in turn makes them a valuable tool for reducing energy use. One of the Penn State researchers shining a light on this side of semiconductors is Chris Giebink, professor of electrical engineering. In his Applied Optoelectronics and Photonics Lab, Giebink leads a team exploring the intersection of optics and electronics.

"We do research in optoelectronic devices, which essentially means semiconductor devices that involve light and electrons," Giebink said. "So, the most common manifestations of that end up being things like light-emitting diodes, which take an electrical current and output light, or solar cells, which take input light and generate electrical power. We do a lot of work with both of those."

Traditionally, most semiconductor work was done with inorganic or "hard" semiconductors such as silicon and III-V materials. However, the work that Giebink does deals mainly with organic semiconductors, which are made up of small molecules or polymers.

"Most inorganic semiconductor folks would call these materials insulators," Giebink said. "But nonetheless, they're very good from an optoelectronic standpoint in terms of being able to emit light efficiently."

They have a variety of advantages over their inorganic counterparts. They are flexible and their emission wavelength (i.e., color of light) is easy to tune throughout the visible spectrum. Given their ease of fabrication, they are potentially cheaper to produce over a large area, and in some cases could even be printed via common printing systems.

Increasing the efficiency and lifetime of organic LEDs is key to Giebink's research and is the focus of several of his lab's projects. Organic light-emitting diodes have a variety of potential applications, such as more efficient solid-state lighting or uses in defense.

"We are working on using integrated LED-photovoltaic stacks for optoelectronic upconversion," Giebink said. "For example, taking infrared light that is plentiful at night and upconverting it so it can be projected in the visible spectrum where you can see it, with the goal of making lighter, more compact night vision equipment."

Giebink is also conducting research into organic and hybrid perovskite semiconductor lasers, especially the creation of a solution-processed laser diode. Currently, laser diodes are only made with hard semiconductors.

"This would open up a whole bunch of different potential applications for us to explore, because these types of laser diodes can be integrated with a wider range of materials and environments," Giebink said. "Such as on silicon, glass, or soft polymeric materials that interface with stuff like skin, for example, situations where it's more difficult to work with epitaxial inorganic semiconductors."

As a researcher, Giebink's work helps to enable a future where organic semiconductors are common. As an educator, he not only teaches his undergraduate students the fundamentals of semiconductors but also works to build enthusiasm in them for a career in semiconductors.

> “Education is one of the major goals of the CHIPS Act,” Giebink said. “So, in the courses that I teach and the labs that I am involved with, in terms of educating undergraduates, what I do reflects the question of ‘how do we connect better with students about semiconductors and the industry?’ And ‘how do we get more people excited about that area of coursework?’”

These students may someday work on improving not just the semiconductors themselves but also improving their manufacturing. Giebink gave an example of manufacturing solar cells for use in space such as on satellites, and a technique that could enable the manufacture of these solar cells at a much lower cost.

“We take existing wafers that are already grown and divide them up into a zillion tiny little cells as small as a grain of sand,” Giebink said.

The next step is to pick each of them up and transfer them onto a piece of glass to form an array, then wire them together, and finally place a thin lens layer on top. Light is concentrated on each of these small cells, which enables a significant reduction in cost because it takes a much less expensive semiconductor to generate power over a given area.

"We’ve demonstrated small-scale proof-of-concepts, but it’s a major processing and fabrication challenge to scale up to large areas,” Giebink said. “We want to bring it up to the point where you can do it reliably at a much larger scale to equip the thousands of satellites that will be launching in the next few years. The type of question that we are facing is not ‘can it be done,' but how do you scale it up? That is the challenge we must solve.” ■

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Credit: Adobe Stock

Growing tomorrow's semiconductor chips in the materials garden

Credit: Nate Follmer

IN SOME WAYS, Mauricio Terrones is a gardener. An Evan Pugh University Professor and The Penn State Verne M. Willaman Professor of Physics, Terrones does not grow flowers or vegetables, but instead, one- or few-atom-thick two-dimensional (2D) materials. Specifically, creating materials with specific properties. The first 2D material ever created was graphene, and Terrones was a pioneer in developing 2D materials beyond graphene such as molybdenum disulfide (MoS_2) and Tungsten disulfide (WS2). These are layered 2D materials, monolayered, bi-layered, tri-layered or more.

And like with gardening of plants, controlling the growth of 2D materials is important.

"My work involves controlling the growth of the monolayers, bi-layers, and tri-layers of these 2D materials," Terrones said. "In addition, my group focuses on controlling the crystallinity and the electronic, magnetic and chemical properties of these materials."

Controlling the growth of these systems can fine-tune them to be efficient semiconductors and improve their performance.

> "These materials are semiconductors, they are atom thick, and it is important to start thinking about growing these materials in a way that can be applied to semiconductor manufacturing," Terrones said. "And do it in a way that we can develop the techniques to quickly characterize them, making them more efficient and unique for the semiconductor industry."

Potential applications of the materials include development of sensors, including quantum sensors. Quantum sensors detect minute variations in magnetic and electrical fields and are made of quantum materials, which are a class of materials where quantum mechanics play a role in their properties and behavior. Practical applications of these leading-edge sensors are many and varied, from communications technology, neuroimaging, electrical and magnetic field sensors, positioning systems, and microscopy, just to name a few.

"Bringing quantum along would be significant because 2D materials could be used for quantum sensing as well," Terrones said. “If you have more effective sensors that are faster and detect very tiny amounts of magnetic fields or chemicals, it could open up many different applications.”

Along with growing materials, Terrones also believes it is important to grow collaborations across disciplines.

“For a problem like we have been facing with semiconductors here in America, you need to bring different disciplines together,” Terrones said. “The multidisciplinary convergent sort of framework for research that we have at Penn State is very important for our success. The idea is to bring together not only researchers here at Penn State but companies, other universities, national labs, and so on, bring them all together to first define the problems, and then tackle them collectively in a faster way than we would without the collaboration.”

This approach, Terrones believes, can also apply to educating students that will grow the semiconductor workforce of the future. This includes giving them practical experience.

“From the student perspective, you want students to understand the problems that industry has, and this can be done by internships in companies and/or national labs,” Terrones said. “Once they understand the problem, they can see the research in a different way. They then can move into the field after they leave here and progress faster because they know the problems in and out and understand the fundamentals. I also believe it is important to bring students together from different disciplines so they are speaking the same language and can move forward developing new technologies and move the semiconductor field forward.”

“I think all of this means that we at Penn State have a unique opportunity to help grow the semiconductor industry and make the U.S. self-sufficient,” Terrones added. ■

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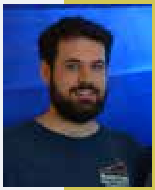
Alumni Impacting America's Semiconductor Future



Daniel Schulman

Integration Engineer, Intel Corporation

What do you do in your current role at your company?

I am a front-end integration engineer at Intel working on the RibbonFET (gate-all-around) technologies. I own a segment of the manufacturing line and am responsible for the technology definition through ramp to high-volume manufacturing.

Please give an example of how a Penn State education has helped you during your career.

My experiences at Penn State set me up for success at Intel. Much of my research was done in the nanofabrication facility and when I started at Intel, I was already familiar with all the common fabrication methods (lithography, etch, deposition) which I still use on a daily basis. In many ways, Intel operates just like the Materials Research Institute and the Materials Characterization Lab. We have a suite of characterization tools at our disposal and my material science background helps me know which the appropriate ones are to solve my current engineering problem.

How do you see the work you do impacting America's future in the semiconductor industry?

There has been significant consolidation in the semiconductor industry and Intel is the only US company developing leading-edge process nodes. Most high-performance semiconductors are entirely sourced from TMSC and Samsung. I am working on one of the first products being offered to external foundry customers. The world needs more supply chain diversity and for this reason, I think Intel will continue to be successful.

Packaging is a huge part of the semiconductor puzzle, and Penn State has answers

THE BIG NEWS around semiconductors, the factor that drove the CHIPS for America Act, was and is the supply chain. Many in the media focused on the shortages and disruption in the chips supply chain that was caused by the pandemic, and in turn, created big increases in the price of things like automobiles. But there is also another big deal happening with semiconductors that does not get as much attention – packaging.

Penn State's material researchers have been working in these areas for a long time, and soon these efforts will get a boost. Penn State has an incoming head of the Department of Electrical Engineering, Madhavan Swaminathan, who will enhance Penn State's efforts in packaging and supply chain research. Swaminathan comes to Penn State from Georgia Tech, where he was the director of the 3D Systems Packaging Research Center, the largest academic center of its kind in the world.

Packaging used to be considered a relatively non-essential part of semiconductor design but no longer. Packaging affects power, performance, cost, reliability, and the basic functionality of chips. It is the container that holds the semiconductor, protects the die (unpackaged, bare chip), connects the chip to a motherboard and/or other chips, and can be used to remove heat.

"These chips have to be packaged for several reasons," Swaminathan said. "One of them is for the chips to communicate with each other and to be able to communicate with the external world. Semiconductor packaging has come into the forefront when it comes to semiconductor chips today. In fact, a major area of investment in the CHIPS Act is semiconductor packaging."

Swaminathan's research is on applications such as wireless communications, both 5G and beyond; high-performance computing for artificial intelligence; and electronics that must operate in harsh environments such as in an automobile or outer space. In assessing Penn State's capabilities with semiconductors, he looks at how the University fits into the semiconductor "ecosystem."

> "There are several layers associated with semiconductors," Swaminathan said. "One of them is the area of the device. And then these devices must come together in the form of circuits. And those circuits then are integrated within a chip and the chip needs to be packaged and ultimately the chips are connected to each other to form a system. So that is the ecosystem that one needs and if you look at Penn State, there are several elements of this already there."

Swaminathan will join the work already being done with packaging at Penn State and help to plan the next steps for packaging research, such as exploring new forms of packaging through work with the Materials Research Institute. This includes quantum computing packaging, which uses glass materials, for example. Such work will require an interdisciplinary effort.

Credit: Corey Beasley and Jennifer M. McCann

"As the department head, I hope to expand quite a bit so that several faculty members both within electrical engineering, as well as other departments, get involved in packaging research," Swaminathan said. "Semiconductor packaging is highly multidisciplinary, where for example we have faculty working from mechanical engineering, looking into stress-related issues centered around reliability. Then you have people from material science and engineering looking into areas related to 2D materials, thermal interface materials, and things of that nature. And then you have electrical engineers designing the system package as well as developing fabrication processes working with other disciplines."

To achieve this, part of Swaminathan's plan is to develop a packaging research center at Penn State, like the one he directed at Georgia Tech.

"The hope is that we are able to create a center at Penn State that is able to come up with capabilities that are complementary to other capabilities that are available within the United States and other universities," Swaminathan said. "We can then take the leadership role when it comes to developing advanced semiconductor packaging that is necessary in the future."

Swaminathan also envisions Penn State playing a role in semiconductor job development. He notes that while people think of technology jobs in the context of someone graduating from the Northeast and moving to the Silicon Valley, technology jobs can be a boon for Pennsylvania and the surrounding region. He points to Intel setting up a plant in Ohio.

"It's really people from places like Ohio, Indiana, Pennsylvania, and others who will be a significant part of the semiconductor workforce and ecosystem," Swaminathan said. "There are people who want to stay near their families for work. It is very, very important to them. So, my belief is that soon, the Mid-Atlantic, the Midwest, these areas are going to grow quite a bit as far as semiconductor-related jobs, which is exceptionally good for these local economies. ■

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Penn State has a head start on building America's semiconductor workforce

A KEY TO AMERICA'S future semiconductor success story will be building a skilled workforce, a well-prepared set of workers to address the needs of the chips industry. Workforce development is an essential part of the Chips and Science Act, designed to meet the needs of the semiconductor industry.

As if they had a crystal ball to see the CHIPS and Science Act coming, Penn State is on it, and has been for a while. Founded in 1998, Penn State's Center for Nanotechnology Education and Utilization (CNEU) is an important driver of semiconductor workforce education. The CNEU works with industry, Pennsylvania four-year universities, Pennsylvania community colleges, and other two-year-degree granting institutions to create degree programs related to semiconductor processing and nanofabrication. According to Osama Awadelkarim, UNESCO Chair Professor and director of the CNEU, this overall effort has evolved into the Pennsylvania Nanofabrication Manufacturing Technology Partnership (PA NMT). The PA NMT is a broad micro- and nano-scale fabrication, synthesis, and characterization educational experience addressing the career needs of students and the technician needs of a wide spectrum of semiconductor-based industries.

The PA NMT partner institutions receive access to resources they would not ordinarily have.

"This is a very expensive kind of training, as it takes resources such as cleanrooms, very skilled personnel, very expensive types of lab equipment, and so on," Awadelkarim said. "Community colleges in Pennsylvania don't have these, in fact, many four-year universities do not. So the idea is to make Penn State's facilities accessible to those institutions who do not have these resources and enable the community colleges and four-year universities map out their own nanomanufacturing education program."

These institutions create their own nanomanufacturing program that includes an 18-credit capstone semester, which is designed with industry partners via the CNEU Industry Advisory Board.

"The capstone is a hands-on immersion for students in micro- and nano-scale fabrication and characterization over 12 weeks taught in CNEU's teaching cleanroom at Penn State's University Park campus," Awadelkarim said. "It is such a great opportunity for students from smaller institutions to take advantage of, this nanofabrication infrastructure of equipment, staff, and faculty resources."

The PA NMT was funded by the state of Pennsylvania for a number of years and incorporates more than 40 Pennsylvania community colleges and four-year universities, with approximately 1,000 students graduating from the program. To meet the workforce needs of the semiconductor industry, Awadelkarim notes that it is vital to draw significant number of skilled workers from female and underrepresented ethnic populations, along with veterans.

"So, since 2018, we have collaborated with historically black colleges and universities, HBCUs, and Hispanic serving institutions," Awadelkarim said. "To date, we have trained 45 students from these groups at CNEU facilities along with about 160 trained remotely. For veterans, we have begun to offer the Nanomanufacturing Certificate Program to veterans recruited from around Norfolk, Virginia. And now, thanks to a $4.7 million grant from the NSF, this is going to be expanded to include Navy, Air Force, Marines, and Army bases in San Diego, Atlanta, and Phoenix."

Credit: Jennifer M. McCann/Penn State MRI

This work has established Penn State as a leader in micro- and nanomanufacturing education and workforce, so much so the NSF created the Advanced Technological Education (ATE) Center for Nanotechnology Applications and Career Knowledge (NACK) at CNEU to mimic the PA NMT model nationwide. This extends the benefits realized by community and technical colleges in Pennsylvania to potentially a national scale, enabling them to provide associate degree level micro- and nanofabrication education. NACK and CNEU have helped in creating more than 10 resource-sharing partnerships that provide the workforce training the United States must have for semiconductor competitiveness.

Along with helping to train students, CNEU also offers the Nanomanufacturing Professional Development (NPD) program for nanomanufacturing-related training of faculty in community colleges and four-year universities as well as incumbent semiconductor industry workers. The NPD began with an in-person training format and was then adapted to web-based live-streaming and fully interactive delivery mode. These were supported by NSF grants.

“The live-streaming delivery mode of the NPD has proven to be very effective in reducing cost and in making the NPD accessible to a much larger group of educators and faculty,” Awadelkarim said. “More than 1,800 educators and industry people have completed the NPD workshops.”

Yet another program to promote semiconductor workforce is the Remotely Accessible Instruments for Nanotechnology (RAIN) service, which offers web access to cutting-edge nanocharacterization tools at 28 partnering institutions in the RAIN Network. RAIN has provided close to 600 remote access sessions to more than 11,000 students.

All of these different initiatives have given Penn State a leadership role in developing strong technical workforce, a key element of the CHIPS and Science Act.

“We’ve expanded what we’ve done in CNEU to a national level,” Awadelkarim said. “So, in other words, we’ve already, even before the CHIPS and Science Act, have been active in semiconductor workforce development. For more than 20 years, we have done this, to the point where if you go to a community college, there is a good chance that they know about CNEU’s work in nanotechnology workforce development because they’ve used our resources.” ■

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Semiconductors designed to deliver extreme capabilities

Credit: Jennifer M. McCann/Penn State MRI

YOUR CELLPHONE PROBABLY would not work very well in space. That is because outer space is full of radiation, and radiation causes defects in electronics that can eventually lead to device failure. You and your cellphone are likely not going to be in outer space anytime soon, but if you are an astronaut relying on electronics to get you to and from space without incident, Rongming Chu's research may one day be key in keeping you safe.

Chu, associate professor of electrical engineering at Penn State, leads research on advancing semiconductors toward extreme capabilities. These capabilities include high operating speeds, high-power handling, and ability to withstand harsh environments, such as the radiation-filled, electronics-hostile realm of outer space.

"Our research largely leverages a relatively new semiconductor material called gallium nitride," Chu said. "Gallium nitride is being used in today's LEDs, 4G base stations, and increasingly in fast battery chargers. My group focuses on new devices and integration technology to take their performance to the next level."

Wide bandgap semiconductors such as gallium nitride are better for radio frequency and power electronics than the material used in most of today's semiconductors, silicon. They are also high in a particular characteristic, radiation hardness, that protects against damage caused by radiation from high-energy rays and particles. Therefore, these wide bandgap semiconductors are especially useful for electronics operating in high-radiation environments, without requiring cumbersome radiation shielding.

In July 2022, Chu led a collaboration with the University of Central Florida, Carnegie Mellon University, and the University of Iowa that received a $7.5 million Defense Multidisciplinary University Research Initiative Award from the U.S. Department of Defense's Air Force Office of Scientific Research. This group included from Penn State Patrick M. Lenahan, distinguished professor of engineering science and mechanics; Miaomiao Jin, assistant professor of nuclear engineering; and Blair R. Tuttle, professor of physics.

"Our research will benefit a lot from collaborations within Penn State, and elsewhere in America," Chu said.

While Chu's research is valuable for America's space program, there is related on-going research that will benefit those of us earth-bound people.

> "In addition to the radiation hardness research, we are working on high-power switches targeting applications in power grids, electric aircraft, and electric ships. This research, supported by the Advanced Research Project Agency – Energy under the Department of Energy and the Office of Naval Research under the Department of Defense, will help us to get more reliable access to the power grid, to use energy more efficiently, and to reduce our reliance on fossil-energy," Chu said.

While this research would lead to applications directly benefiting American society, Chu sees Penn State's role in developing America's semiconductor future as multi-faceted.

"We will contribute to increasing America's role in the future of semiconductors development and production by firstly, creating and maintaining a research/education environment that attracts the best talent from the world," Chu said. "Secondly, developing innovative technologies that have a real path towards market adoption, and thirdly, training the next-generation technologists who will lead continued innovation of semiconductors."■

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Akhil Dodda

Graduate Research Assistant, Das Group

What will be your future role at your company?

I will be joining as a Research Member at Western Digital Research located in San Jose, California.

Please give an example of how a Penn State education has helped you during your career.

Penn State education has been instrumental in developing unique skills that prepared me for a smooth transition from school to work. During my Ph.D. I was exposed to a wide variety of technologies and techniques to advance my understanding of the field of semiconductor devices and through research symposiums like ESM Today, College of Engineering Research Symposium (CERS), MRI's PPG Elevator Pitch Competition, etc. I honed my presentation, communication, and interactive skills. These experiences have allowed me to meet the mighty team of material characterization, electrical characterization, and nanofabrication experts at the Material Research Institute, who were very friendly, approachable, and supportive of my research activities. I feel the experiences and lessons learned are truly valuable and have become a crucial component in shaping my future endeavors.

How do you see the work you do impacting America's future in the semiconductor industry?

With an increasing demand for internet of things (IoT) edge devices and the world transitioning from computing-centric to data-centric, the need for low-power memory-augmented sensor devices have become an important concern, more than ever before. My work focuses on developing new-memory technologies based on novel materials and operating them at low-power for future IoT devices.

Thanks, silicon for everything. Now we need something better.

Credit: Das Group

SILICON HAS BEEN king for a long time in computer technology. It is the namesake for America's technology hub, Silicon Valley. However, silicon is nearing its limit as an effective semiconductor material.

Silicon was driven by Moore's Law, which states that transistors were shrinking so fast that the number that could fit onto a chip was doubling every year, and this in turn would cause computing power to increase and at the same time decrease relative cost. However, silicon can no longer keep up, as performance boosts in new silicon chips are smaller than in previous iterations. Moore's Law has ended as silicon can no longer accommodate additional transistors, and it would not be good for technology and society in general if we do not have an alternative material ready to replace it. We also need to make the computers more energy-efficient and sustainable since their exploding numbers can be a threat to climate change.

Enter two-dimensional materials as a potential savior, and Penn State researchers such as Saptarshi Das, associate professor of engineering science and mechanics, who are part of the search for the silicon replacement.

> "My group is working on making semiconductor devices, mostly for sensing, computing, storage, and security applications," Das said. "We are trying to really push the technology so that it can be low power and at the same time high performance. To do that we are working on novel materials, and in this particular case, it is a two-dimensional material. The fact that they are ultra-thin makes it possible to scale these devices more aggressively than what you can do with the current silicon technology."

Das notes that while semiconductors are ubiquitous now, with chips in everything from refrigerators to cars to the phones we always have on hand, they are only going to become even more common. However, Das stresses that these devices of the future must be sustainable and low-power.

"If you think about the total number of semiconductor devices, including now cloud computing, IoT devices, and so on, they are making our life very easy, but at the same time, they're also very energy hungry," Das said. "Each social media post that you make or a WhatsApp image that you send has an energy cost associated with it, while it is negligible for one post or image, when combined at a global scale, we may run into energy challenges. And this is increasing on an exponential trajectory, and it is not going to stop, because we do not want it to stop. It makes our lives so much better and easier. So we need to find solutions that are energy sustainable."

Das's research group focuses on making the devices that will drive this future, part of what he sees as a wide spectrum of semiconductor research and innovation at Penn State. Another part of this wide spectrum is the National Science Foundation-supported user facility, the Two-Dimensional Crystal Consortium, which works to create the materials needed to make the next generation of semiconductors chips.

"There is natural synergy between the materials folks and the folks like us who are trying to make the next generation of devices," Das said. "At the same time, we have state-of-the-art nanofabrication and characterization facilities. Also, once you have the devices you are thinking about, you need to make circuits, architectures systems, and then you have to think about packaging. At Penn State, we have faculty covering this wide spectrum across the layers of our semiconductor ecosystem, and this positions us very strongly in terms of semiconductor research at Penn State."

Another aspect of the semiconductor puzzle that Das sees Penn State as a contributor is improving the semiconductor workforce development. The recent pandemic-induced chip shortage can be, Das notes, an even worse problem in the future if we fail to develop the critical workforce for semiconductor manufacturing.

"Technological superiority still exists with the U.S. but when it comes to manufacturing semiconductors, it is mostly offshore," Das said. "We have to develop our semiconductor workforce. We have seen during the pandemic, you know, what happens when you have a chip shortage, right? When the production goes down, if we have too much reliability on a very small number of key players, such as the companies like Intel and TSMC, it is not good and shows a need for a plan B."

Plan B is having more and newer companies coming in and starting to manufacture advanced semiconductors, Das said, and that includes developing an American semiconductor workforce. Das notes that the CHIPS Act is a good first step towards this "Plan B."

"I think universities like Penn State and the existing semiconductor industry have to partner up because I don't think universities can alone do it, nor can the semiconductor industry," Das said. "There is an urgent need, so we need to get started as soon as possible on this thing, otherwise, it's going to be too late."■

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Credit: Das Group

A semiconductor that could alleviate computing's climate problem

Credit: Corey Beasley

WHILE A LOT of the focus on fighting climate change lands on things like gasoline vehicles and factory emissions, computers gobble up plenty of carbon-based energy on their own.

“If we could reduce the energy cost of computation, we could lower global warming,” said Susan Trolier-McKinstry, Evan Pugh University Professor, Steward S. Flaschen Professor of Ceramic Science and Engineering, and professor of electrical engineering. “Computing consumes a huge fraction of the overall energy budget of the world. It is currently above 10%. It is projected to go to 21%. If we could lower the energy costs for computing that would have enormous implications in terms of climate change.”

Trolier-McKinstry's semiconductor research is focused on doing just that – lowering the energy needed for computing. The way her work directly impacts semiconductors is around non-volatile memory, which is memory that can retain stored information even after a power source is removed. Current computers operate using what is known as the Von Neumann Architecture, first described in 1945 by mathematician and physicist John Von Neumann. This architecture’s key feature is that the memory chip and the processing chip are separate from each other.

“If you look at the current energy cost and time cost of computing, a very significant fraction of that cost is associated with the fact that the memory chip and the processing chip are physically separated in the system,” Trolier-McKinstry said. "That was a decision made by von Neumann decades ago, and it's served us really well to this point.”

However, given the ubiquity of computers that will only increase, a better system is needed.

> "Today, the estimates are that up to 80% of the time cost and a considerable fraction of the energy costs for computing is associated with getting data back and forth between the memory and the processors or between processor units,” Trolier-McKinstry said.

Trolier-McKinstry is the director of a center at Penn State, the 3-Dimensional Ferroelectric Microelectronics (3DFeM), that is working to solve this issue.

“One of the main goals of this center is to change that paradigm to build the memory right on top of the processor unit so that you take away that extra energy and time burden,” Trolier-McKinstry said. “Using ferroelectrics also makes the memory non-volatile, so you do not have to keep rewriting it and then pay the energy costs every time associated with writing that memory. As a center, we are working on how to change the Von Neumann paradigm to enable low-energy cost computation.”

Trolier-McKinstry is also the director of the Center for Dielectrics and Piezoelectrics (CDP), a National Science Foundation Industry/University Cooperative Research Center. Both centers complement each other as a significant part of the semiconductor research effort at Penn State.

"To make a circuit function, you need both the active materials, which is what 3DFeM addresses, and all the passive materials, which is what CDP addresses,” Trolier-McKinstry said. “With the 3DFeM, we have many major U.S. players and several of the major international players in semiconductor production involved directly in the center. Through CDP, we have pretty much every multilayer ceramic capacitor supplier.”

These relationships between Penn State and industry are beneficial for the U.S. semiconductor industry, Trolier-McKinstry said.

“Using a different material set, Texas Instruments is currently one of the leaders in development of non-volatile memories,” she said. “We think we have better material, but they already have all the circuit designers. Because we interact with all the key players in manufacturing, we hope to see the manufacturing of these types of semiconductors occur in the U.S.” ■

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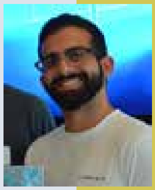
Alumni Impacting America’s Semiconductor Future



Joseph Nasr

Senior Process Engineer at ASMA

What do you do in your current role at your company?

I am currently a Senior Process Engineer at ASMA, located in Phoenix Arizona. ASMA is a top notch ALD company. Basically, I work closely with the “semiconductor titans” and I provide high volume manufacture (HVM) solutions to enable next generation transistors. This means working on developing film recipes, understanding tool’s hardware and implications to in-wafer performance. I develop DOE to establish the best parameter combinations.

Please give an example of how a Penn State education has helped you during your career?

The most important skill I got from my Penn State education was strong communication skills. During my Ph.D. years, I was able to collaborate with numerous groups within Penn State and other universities. I am strong believer that Penn State has a variety of centers (i.e. 2DCC, ATOMIC), which helps you to build good communication skills and team work mindset.

How do you see the work you do impacting America’s future in the semiconductor industry?

ALD films are the toughest and most complex films humanly possible. The fact that my contributions can be used in the next generation electronics (i.e. iPhones), gives me a strong feeling of accomplishment.

Credit: Seana Wood/Penn State MRI

'Highly perfect': Meeting the challenge of making 2D semiconductor materials

TWO-DIMENSIONAL MATERIALS ARE vital for the type of semiconductors that will push the future of electronic devices and energy-efficient lighting, but they are a challenge to make. They must have very few defects, difficult given their very small, nano-level size.

Helping Penn State pull off the synthesis of these hard-to-produce materials is Joan Redwing, director of the National Science Foundation-sponsored Two-Dimensional Crystal Consortium (2DCC) – Materials Innovation Platform, and distinguished professor of materials science and engineering and electrical engineering. In these roles, Redwing plays a key part in Penn State's semiconductor research.

"I work on techniques for making thin films of semiconductors, along with making nano structures like nano wires and two-dimensional films which are also very small in size," Redwing said. "My research focuses on understanding these processes at an in-depth level so that we can control the properties of the semiconductor material, which is vital because the semiconductor needs to be highly perfect, with no missing atoms or other defects. I study how to control the synthesis of materials at that level so that we can achieve highly perfect films that then are used in electronic and optical devices."

Redwing and the 2DCC's work in synthesizing semiconductor materials is a practical benefit for other semiconductor researchers, as they make the difficult-to-create materials that drive semiconductor research forward.

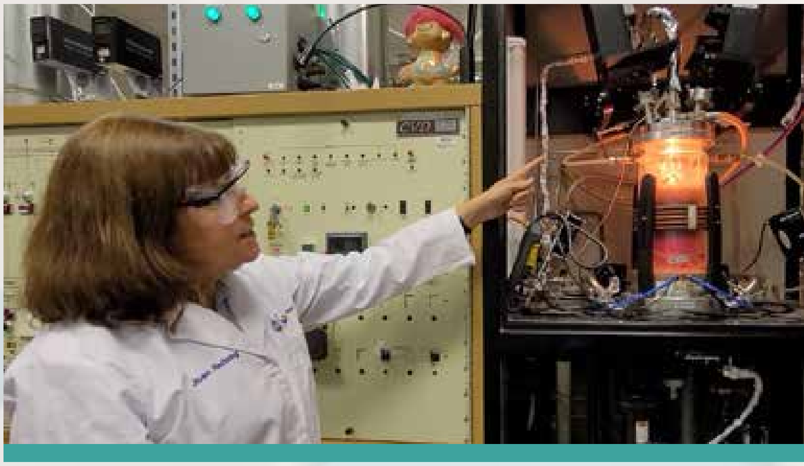
"The materials that my group makes are used by a variety of other researchers at Penn State, who are working on device fabrication, doing characterization of the materials or process development," Redwing said. "My role is to advance the materials themselves; to develop new materials and structures and to improve the quality of existing materials that we have in support of making better semiconductor devices."

This is not limited to Penn State. The 2DCC not only provides these materials to Penn State researchers but works with semiconductor experts from industry and higher education institutions beyond Penn State.

> "The 2DCC is a national user facility funded by the National Science Foundation," Redwing said." That means we have researchers from outside of Penn State who either use the materials that we make, or they come on site to make materials for their own research. So, that is a big way that we collaborate with researchers outside of Penn State."

Semiconductors are Redwing's life work. She began her career researching the semiconductor material gallium nitride, playing a part in the development of these materials for use in blue-light emitting diodes which is the basis for all of today's LED lighting. Currently, one of Redwing's specialties is the main manufacturing technique for making gallium nitride materials for device application – metalorganic chemical vapor deposition.

The ubiquitous use of LED lights in so many applications makes gallium nitride an important semiconductor material, similar to silicon.



Credit: Seana Wood/Penn State MRI

"LEDs have so many uses, more than just lighting your house or as decorative lighting," Redwing said. "For example, they are used in backlighting of displays in cell phones and laptops which has enabled the displays to become much thinner and lighter weight than in the past. These are just a few of the tremendous number of ways in which developing new semiconductor materials like gallium nitride have enabled us to have new devices and new applications that we just would not have otherwise."

Redwing notes that many of the students who have passed through her research group have moved on to semiconductor-related careers, many of them with Intel. Given that semiconductors are only becoming more important as applications such as the growing use of smart devices, they provide a variety of employment opportunities that will only increase with the CHIPS Act becoming law.

"I am really excited about the CHIPS Act passing because this is going to give my students even more opportunities in the future," Redwing said. "A lot of the U.S. semiconductor companies were not only doing manufacturing abroad but also a lot of their R&D, so my students were losing job opportunities in the U.S. I am happy that the U.S. is making this investment. The public should understand that semiconductors are as important, if not even more important, for our society's future as oil and gas are now." ■

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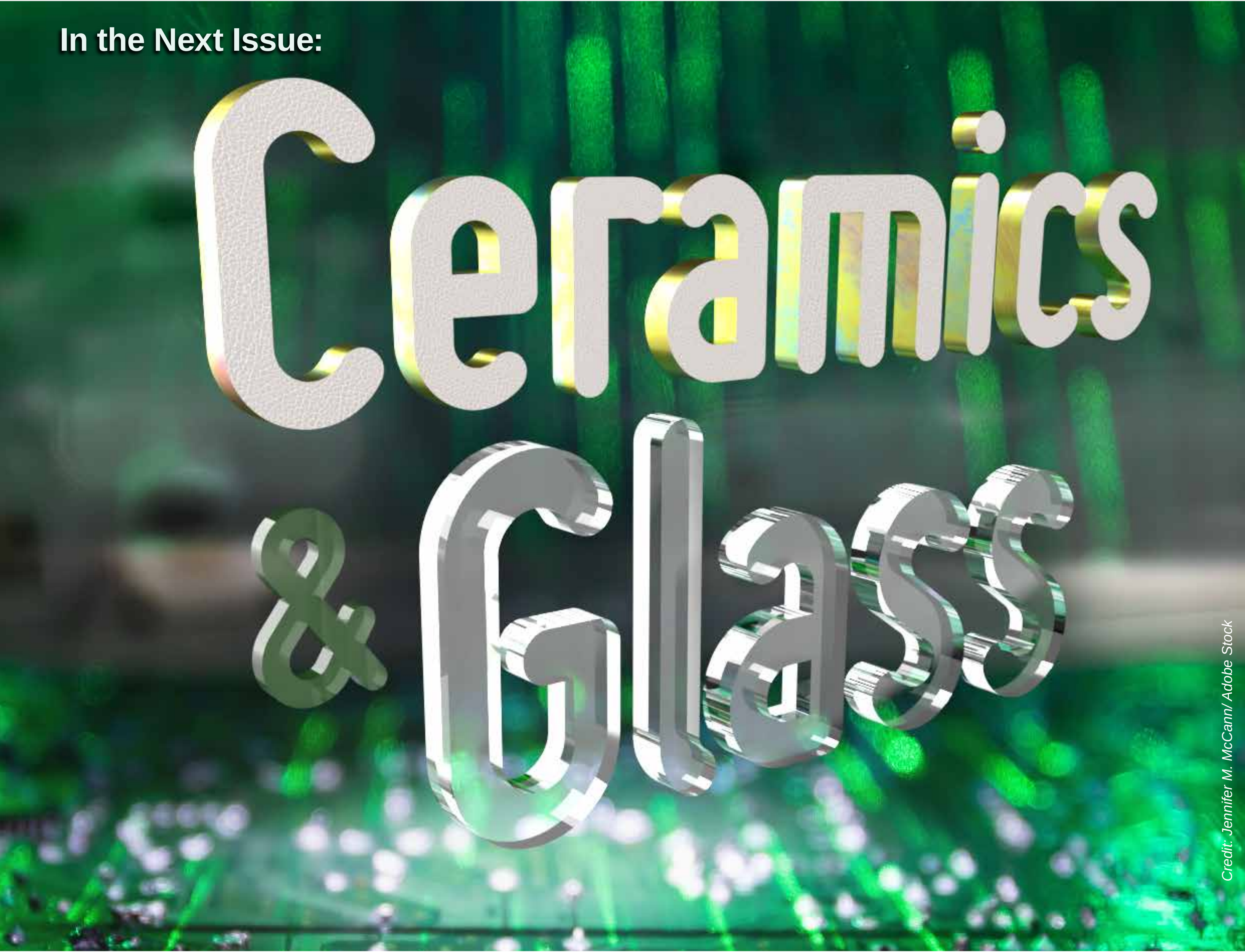

Credit: Jennifer M. McCann/ Adobe Stock